How to validate MODELS AND SIMULATIONS

The complexities of SPECIES INVASIONS

Flu and RSV return as POST-COVID INFECTIONS

AMERICAN Scientist

January–February 2023

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Bringing Up Dino



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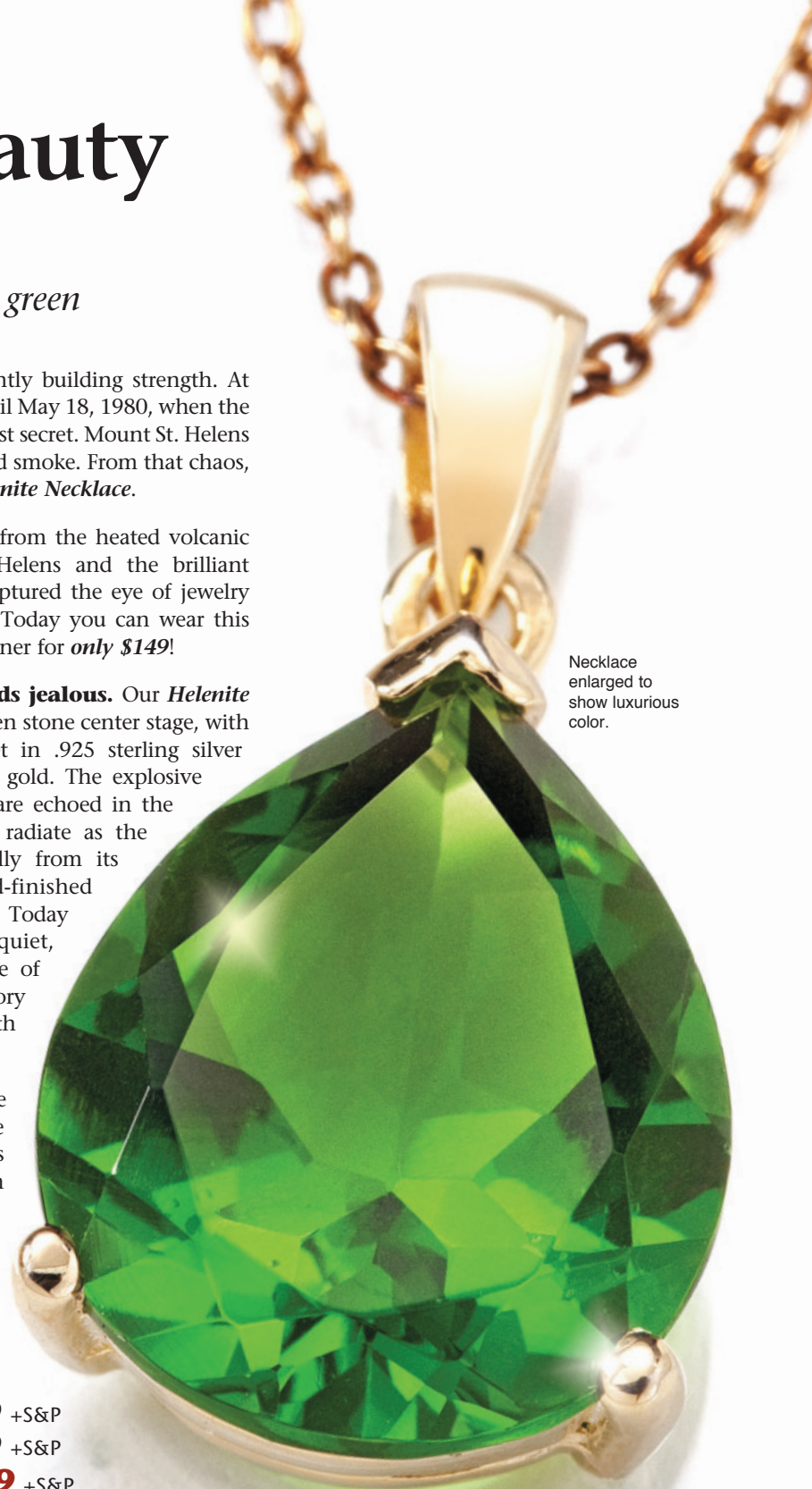
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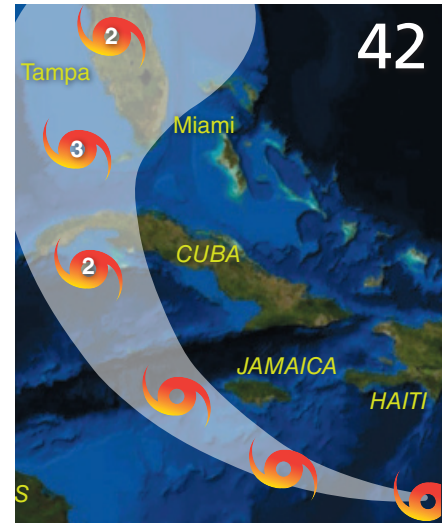
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Edward A. Wasserman

The Cover



An adult theropod dinosaur in the genus Deinonychus *sits with its recently hatched baby. In recent years, paleontologists have learned that this dinosaur laid blue-green eggs and likely incubated them in partially exposed nests, much as many modern birds do. New fossils and innovations in research have begun to answer questions about dinosaur reproduction that were once thought to be unattainable, such as nesting strategy, egg color, egg incubation time, parental care, or eggshell texture. In "A New Picture of Dinosaur Nesting Ecology" (Perspective, pages 18–23), paleontologist Daniel T. Ksepka offers an overview of these sweeping advances in his field, showcasing the spectrum of reproductive traits among the dinosaurs, often with surprising mixes of reptilian and avian traits. (Cover illustration by Sean Murtha.)*

Collect New Data, Revise, Repeat



If you grew up visiting natural history museums, you probably think you have a good sense of what dinosaurs looked like, and the posed displays probably gave you an image of how they behaved. But recent studies of dinosaur eggs may shift your mental picture of these diverse creatures. In this issue's Perspective column, "A New Picture of Dinosaur Nesting Ecology" (pages 18–23), paleontologist Daniel T. Ksepka discusses findings of certain dinosaur eggs with soft shells, a feature more like modern turtle eggs than birds or crocodilians. Startlingly, it's likely that the very first dinosaur eggs were also soft-shelled. It had long been assumed that all dinosaur eggs were hard-shelled, like their modern evolutionary descendants. It's likely that hard-shelled eggs arose in three different lineages independently, rather than from a single ancestor. And some hard-shelled dinosaur eggs have been revealed to have had colors, a feature that arises when eggs are in partially exposed nests rather than buried underground, which is more of a birdlike trait. Perhaps it should not come as a surprise that dinosaurs would have some traits that are more like birds, other traits that are more reminiscent of reptilians, and yet others that are uniquely their own, not found in either. As Ksepka notes, "Evolution doesn't always align with easy assumptions about early and modern traits."

Shifting perceptions in research can alter the way that we look at many species. In "Is Garlic Mustard an Invader or an Opportunist?" (pages 34–41), ecologist Michael Anderson takes a different view of what has commonly been thought to be an invasive plant, deserving of eradication, because early studies found diminished numbers and diversity of native plants in its presence. Much research has now been devoted to determining whether garlic mustard outcompetes local plants, or if it just took advantage of the sweeping changes in the ecosystem that humans have made over the past few decades. If it's more of an opportunist, ecologists and land managers may need to rethink their perception of this plant as a weed that needs immediate and thorough removal. Anderson observes that "the spread of garlic mustard might be an effect rather than a cause of changes that are occurring in native ecosystems. The plant may largely be riding on the coattails of favorable environmental changes driven by humans."

New data can also update the accuracy of mathematical models, which are often used to make predictions and to provide recommendations to decision-makers, so these simulations need to produce verifiable results as well as they possibly can. In "In Models We Trust—But First, Validate" (pages 42–49), data scientist Daniel Solow discusses the different methods that can be used to evaluate the output of mathematical models, including common-sense reality checks, comparisons to experimental data, updating of parameters, showing confidence intervals, or performing sensitivity analysis. Solow reminds us that "Regardless of the amount of validation, one must accept some degree of uncertainty with model predictions, so some amount of skepticism is always warranted. The more you know about how a model is validated, the better you can decide how much to trust its predictions."

How do you try to keep an open mind in your research, as trends shift? Write to us and let us know.
—Fenella Saunders (@FenellaSaunders)

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Wicked Crosswords

To the Editors:
I have always enjoyed reading Henry Petroski's essays, especially his recent one on crossword puzzles (Engineering, September–October 2022). Indeed, the principles of Taylorism have encouraged me to try to summarize the similarities between solving crossword puzzles and scientific problems.

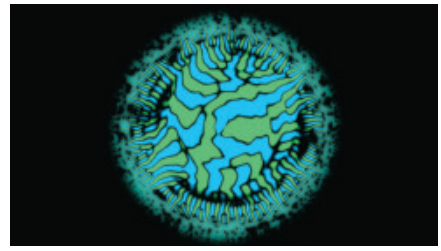
First, some scientific principles (such as Newtonian mechanics), like some puzzles (such as the Monday *New York Times* crossword), are straightforward. Conversely, some are more complex (such as quantum mechanics and the Saturday puzzle). Some answers to both scientific questions and puzzle clues require interdisciplinary effort—for example, if the answer is *bauplan*, you need to know some German. And some questions may have multiple equally plausible solutions. In research, there are competing theories, whereas for example in a puzzle, if given the clue "steep rock face" and the bridging letters L, F, and F, the answer could be either "cliff" or "bluff." Finally, some puzzles and scientific questions are simply unsolvable, being beyond the knowledge of you and your network.

Recently, your magazine mentioned *wicked scientists* ("The World Needs Wicked Scientists," July–August 2022). I wonder if there is an analogous "wicked crossword solver"?

Leo W. Sham
Hong Kong

Turbulent Art

To the Editors:
Zellman Warhaft's "The Art of Turbulence" (November–December 2022) was a delightful read for me. For many years, I have dealt with the world of turbulent fluid flows associated with the engineering design and development of turbomachines, such as turbines and jet engines. It was a pleasure for me to see such flows rendered in text and in the artistic paintings and photos in the article.



One of the article's referenced authors, Nobel Prize winner Richard Feynman, has been quoted as stating, "Turbulence is the most important unsolved problem in classical physics." The art in "The Art of Turbulence" deftly shows the importance of Feynman's statement. The art also makes clear the illuminative rhyming verse on turbulence, given in 1922 by mathematician and physicist Lewis Fry Richardson:

> Big whirls have little whirls,
> That feed on their velocity;
> And little whirls have lesser whirls,
> And so on to viscosity.

Lee S. Langston
Manchester, CT

How to Write to *American Scientist*

Brief letters commenting on articles appearing in the magazine are welcomed. The editors reserve the right to edit submissions. Please include an email address if possible. Address: Letters to the Editors, P.O. Box 13975, Research Triangle Park, NC 27709 or editors@amscionline.org.

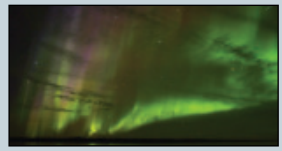
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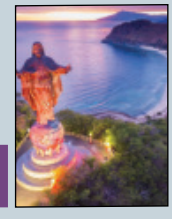


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Paula Cushing studies arachnids of all kinds, from ones that never stop hunting to ones that use morbid costumes to avoid being eaten.
www.amsci.org/node/5012

Tackling Neurological and Psychiatric Diseases
Kurt Marsden, assistant professor in the department of biological sciences at North Carolina State University, says three-quarters of our known genes are needed to create our human brains. In a presentation for Sigma Xi's Science by the Slice series, he discussed the connection between those genes and how our brains function, including in learning, response behavior, and after exposure to chemicals or infectious diseases.
www.amsci.org/node/4987

Tricks or Treats
Our guts differentiate between sugar and artificial sweeteners. Duke University sensory neurogastroenterologist Melanie May Kaelberer discussed her research on the gut-to-brain connections at Science by the Slice. Check out the From the Staff blog for a roundup of the event, including a video of the entire presentation.
www.amsci.org/node/5011

Race-Related Experiences and Well-Being
Mental health risks among people of color have been exacerbated by modern pressures such as social media and the COVID-19 pandemic. Shauna Cooper, director of the Strengths, Assets, and Resilience Research Lab at the University of North Carolina at Chapel Hill, discusses how race-related experiences and inequities affect the well-being of racially and culturally diverse children and families.
www.amsci.org/node/4988

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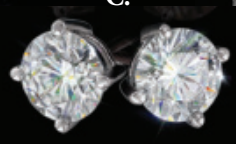
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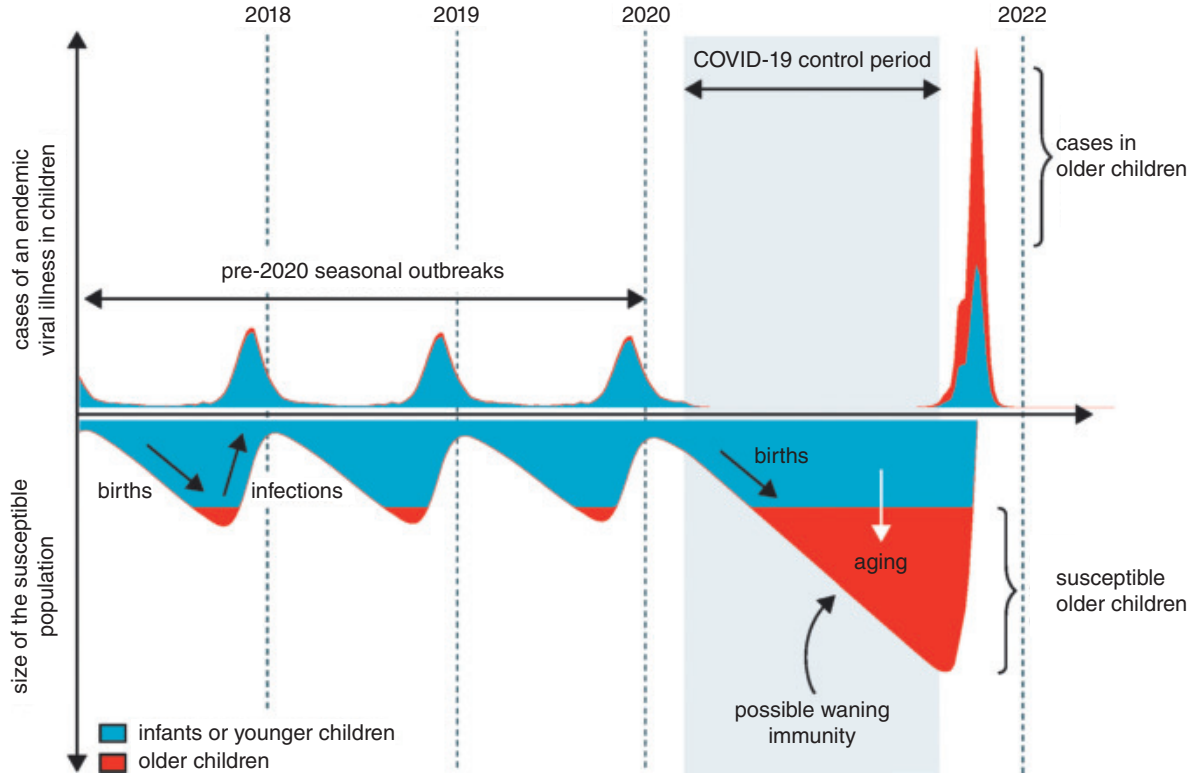
The seasonal infections that would have happened over three years have been hitting all at once. What can researchers learn?

In the wake of the COVID-19 pandemic, we are now seeing a highly unusual pattern of seasonal respiratory infections. The influenza and respiratory syncytial virus (RSV) seasons started earlier and spiked higher than usual in 2022. Hospitalization rates for flu are the highest seen in a decade in the United States, and pediatric hospitals in particular have been at or near capacity. The COVID-19 pandemic has changed so much in public health. "We've never studied respiratory viruses, especially the common respiratory viruses, in such great detail before," says Vijay Dhanasekaran of the University of Hong Kong.

The cumulative load of infections that would have happened over three years have hit all at once. As people changed their behaviors to avoid transmitting SARS-CoV-2, rates of flu and RSV dropped to near zero over the past two to three years. "Before the pandemic, I don't think I ever would have guessed that in the absence of vaccines or therapeutics, that based on changes to our behavior alone, we could basically wipe out two flu seasons," epidemiologist Stephen Kissler of Harvard University says. As human populations and viral populations come together again after this unprecedented period of separation, we're seeing new patterns of infection. That creates complex issues from a public health perspective, but also unwitting case studies that reveal new lessons and information about how these viruses operate.

Flu and RSV usually follow a seasonal pattern, peaking in the winter when conditions are cold and dry in temperate locations, and peaking close to the rainy season in tropical locations. RSV mostly affects children under two years old and the elderly; for most other people, getting infected feels like a common cold. First infections in young children, before they've developed immunity through an exposure, can be more severe. Epidemiologist Rachel Baker of Brown University says that, absent the weird dynamics introduced by the COVID-19 pandemic, "RSV is a very regular disease in terms of the timing and the size of the seasonal outbreak, at least compared to something like influenza, where we always have this slight surprise each year of how severe the outbreak is going to be and how well the particular strain that's circulating matches what we prepare for the vaccines. RSV's evolution doesn't tend to play as much of a key role as it does for influenza."

(*continued on page 8*)



This general model of virus circulation in children shows how behaviors to control the COVID-19 pandemic disrupted transmission of other respiratory infectious diseases, so that a large group of children susceptible to those disease accumulated over time, creating the conditions for large and early outbreaks when pandemic mitigation measures were lifted.

K. Messacar et al., 2022. *Lancet.* 400:1663.



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The two-year break in human exposure to influenza has had notable effects on the flu virus. Flu infects many adults and children every year, evolving quickly and traveling efficiently around the world. "Influenza viruses would behave a certain way before the pandemic because they migrate really quickly," Dhanasekaran says. "Now the biggest issue is the unpredictability of the evolution." As travel declined during the pandemic, flu strains diversified. Rather than one strain that dominated globally, different strains evolved and circulated in particular locations, as Dhanasekaran and coauthors documented in a March 2022 paper in *Nature Communications*. This unpredictability has made vaccine development more challenging. Three separate strains lost genetic diversity and were largely confined to outbreak hot spots in South and Southeast Asia, China, and West Africa, and one strain that was already declining before the COVID-19 pandemic seems to have gone extinct. Nevertheless, this year's vaccine targeting four major flu strains is effective and the best protection at our disposal during this epidemic. In the future, mRNA vaccine technology could circumvent these problems.

Hong Kong hasn't experienced a flu outbreak since February 2020, providing an interesting case. Dhanasekaran points to widespread mask wearing as the reason why. "By February, we had almost 99 percent of people wearing face masks in public," he says. "So, in Hong Kong we immediately saw a complete decrease in influenza much earlier than the rest of the world." Wearing masks in public continues to be nearly unanimous and unpolitical there, even though it is not mandatory. These big drops in flu prevalence surprised many epidemiologists, and we now know far more about medical face masks, improved ventilation, and other mitigation measures.

Among young children, a large group who had never gotten RSV has now been getting the virus all at once. "When you have a large susceptible population like we have right now, then more kids are getting infected," Baker says. "Those kids are spreading it to more of their peers. And so there's this ripple effect through exponential growth that happens, a multiplier effect." Importantly, all these kids would have gotten RSV anyway—what's unusual is that they're all getting it at once, rather than spread out over several years (*see the figure on page 6*).

Baker contributed to papers that warned of the coming surges, including one in the *Proceedings of the National Academy of Sciences of the USA* in November 2020, and another in *Lancet* in September 2022. Hospitals and health departments struggled to prepare at a time when the pandemic was in full force and health care workers were quitting their jobs in record numbers.

There are always regional variations in these viral spikes, and this year's unusual pattern offers an opportunity to understand them better. Factors that seem to affect this variation, for RSV, include absolute humidity and past and current patterns of nonpharmaceutical interventions, according to Baker's research. RSV normally follows a latitudinal pattern, with warmer places tending to see spikes first and for longer. For flu, regional variation may be affected by what strain is circulating, vaccine uptake, the prevalence of wearing masks and taking other precautions, and winter or rainy season onset. Those seasonal rhythms can be shifted off course when other dynamics increase transmission. "When you have a larger pool of kids who don't have immunity to the disease, that tends to override seasonality," Baker says. "Much like in a pandemic, you can get outbreaks at any time of year."

Hong Kong hasn't experienced a flu outbreak since February 2020.

Not every state has had a problematic RSV outbreak so far. Places heavily hit include Colorado, New York, Oregon, Pennsylvania, Rhode Island, and Washington. Researchers like Baker are trying to understand why—how much this variation is because of human behaviors that currently reduce transmission, variations in immunity because of how long nonpharmaceutical interventions were in place and how they were lifted, and climate effects.

The surges seen in the United States have occurred in other places in the world, too. For example, RSV swept through parts of Australia in late 2020 as schools reopened and other mitigations were lifted, documented in a May 2022 paper in *Nature Communications* led by the Australian RSV study group. "When children don't mix with each other, viruses can be carried in smaller groups of children," explains Dhanasekaran, one of the authors on that paper. "And then once things open up, an epidemic gets going really quickly. That's what we saw in Australia." A study about what happens when a large, uninfected population suddenly mixes with a wild virus would never be ethical or feasible in a lab; studies like this one are significant, because of the unique situation the COVID-19 pandemic imposed.

This unfortunate situation is allowing researchers to answer another big question about RSV: What affects the severity of the infection? Data show that, after the COVID-19 pandemic, children are getting RSV for the first time at older ages. Now researchers can investigate: Are older children less likely to be hospitalized, or is the same proportion of children at any age at a heightened risk of hospitalization when they are infected with RSV for the first time? That information could help caregivers and health care workers make better informed decisions about protecting children. And in the coming years, preventing many severe RSV cases will be possible. Two vaccines and a monoclonal antibody injection for RSV are on the horizon, with pharmaceutical companies GSK and Pfizer hoping to roll out vaccinations for pregnant people and the elderly in 2023.

An important tool for responding quickly to outbreaks and pandemics is genomic and serological surveillance of pathogens. Here, the COVID-19 pandemic has also been an impetus for improvements. "I'm hoping that people use the capacity that was built for COVID-19 and then transform it toward other pathogens," Dhanasekaran says. "Sequencing technology has become cheaper and cheaper, and lots of middle income countries are moving toward that." Twenty or so years ago, a handful of genomes would have been available for coronaviruses or influenza, monitored only in major cities in the richest nations. "Now we have millions and millions of genomes for analysis," Dhanasekaran says. We've come a long way, and as we learn lessons from these outbreaks, it will be possible to do far better next time.—*Katie L. Burke*

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Chemistry at the Quantum Level



Courtesy of Yosuke Kanai

As a professor of chemistry at the University of North Carolina at Chapel Hill, Yosuke Kanai does research in theoretical and computational chemistry that is centered on developing quantum-mechanical computational methods and using them to study the dynamical behavior of complex chemical systems. His work on simulating quantum-mechanical processes spans a wide range of topics from solar energy conversion to proton beam cancer therapy. The overarching theme of his research is to develop predictive understanding of electronic excitation and dynamics phenomena that arise from the interplay among electrons and atoms, especially in condensed-phase and other extended systems. He is particularly interested in obtaining understanding at the molecular level by developing and applying computational methods based on first-principles electronic structure theory. He received his PhD in theoretical chemistry from Princeton University. Kanai gave the inaugural Sigma Xi Pariser Global Lectureship for Innovation in Physical Sciences in April 2022. After the event, he spoke about his research with American Scientist *editor in chief Fenella Saunders. This interview has been edited for length and clarity.*

How is quantum chemistry connected to quantum mechanics and theoretical chemistry?

In the early 1900s, the concept of theoretical chemistry emerged. Essentially, instead of performing experiments, we can use mathematics and physics to figure out how molecules behave under different conditions. Within theoretical chemistry, there are a couple of different subfields, including quantum chemistry. What quantum chemistry comes down to is using the fundamental physics of quantum mechanics to understand how molecules behave under different circumstances. If you go down to the scale of atoms or molecules, you have electrons and atomic nuclei. Instead of electrons behaving like classical particles, the electrons follow quantum mechanics. Also, some parts of atomic nuclei, such as protons, are also very small and need to be treated quantum mechanically. When quantum mechanics became rather mature in the 1920s, many scientists realized that they could actually use the laws of quantum mechanics to understand how electrons and atomic nuclei behave. Even though it started a long time ago, electronic computers made it possible to actually use quantum mechanics, to apply it to study molecules. That started out in the 1950s, and with all the advances in computers in the past 70 years, we've seen more and more interesting developments and advances in the field of quantum chemistry.

Is quantum chemistry more about the interactions between particles, whereas quantum physics is more about the behavior of fundamental particles?

Quantum mechanics is a very broad field. On the one hand, you have a lot of high-energy physicists applying quantum mechanics to make sense of subatomic particles that are fundamentally related to understanding the overall structure of the universe. But on the other hand, you go to the really tiny scale of electrons and molecules, and we're using quantum mechanics in the context of understanding how electrons and atomic nuclei behave.

How have technological advances affected this field?

It started with the development of electronic computers in the early 1950s. In the 1990s people started having more access to personal computers. Certainly that motivated people to explore fields like quantum chemistry, because now they could start to perform quantum chemistry calculations on their personal computers. And then of course you also see a lot of excitement about supercomputers. The continuing advancement of computing technology is pushing back the frontiers for quantum chemistry. But that's one side of chemistry as a whole field, because on the other side, it's not like experimental chemistry has stopped advancing. In the past 50 years or so, on the experimental side, people have started having things like particle accelerators and beam lines for doing spectroscopic experiments. If you have a lot of advancement on the experimental side, then you're able to obtain a lot more exciting results, and that motivates people like myself to understand what's happening in experimental chemistry. In a way we all advance hand in hand.

Is it possible to produce an accurate model at the scale of particles?

Particularly because of that tiny scale, it's difficult. We know how to use Newtonian physics very well. If you want to model how I throw a ball, you know exactly where that ball is going to go. When you go to a tiny scale, it's no longer Newtonian physics but quantum mechanics that governs behavior. That makes it very complicated to understand and predict what happens on that tiny scale of molecules. We can't obtain an exact solution. But thanks to advances in computing technology, we can be pretty accurate for some properties, such as predicting reaction energy. Some other properties, like the optical excitation energy, are more difficult to predict accurately. For organic molecules, we're able to reliably model those optical excitation properties like transition energy. But for some other types of molecules, such as transition metal molecules that contain heavy mass elements, it's difficult for us to model optical properties reliably. It's also partly because of relativistic effects and those things becoming important. So there are certain properties we can model more reliably than others, but also certain groups of molecules we can model more reliably than others.

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Why do you work on characterizing high-energy proton beams?
This physical phenomenon is important in cancer therapy. But it's also important for space missions. If you go outside of the Earth's atmosphere, you have these galactic cosmic rays of high-energy ions going by. If you're an astronaut and you're not protected, you'll be hit by them. One of the big problems for space missions is that electronics must be protected from cosmic rays, because high-energy ions can pass through electronics and induce electronic excitation, so your electronics can fail. So understanding the behavior of high-energy ions becomes very important in different contexts.

How do simulations give insight into the behavior of these high-energy beams?
To do experiments, you want to produce these high-energy protons artificially, which can be done using a cyclotron, which can accelerate the proton into a charged particle using magnetic fields. You can measure things like electronic stopping power, which is essentially the rate of energy transfer from these high-energy protons to electrons in the target matter, like DNA. But what is difficult for experimenters to figure out is where this energy is transferring into the DNA. If you look at the structure of DNA, it's a very complex macromolecule. The quantum mechanical simulations we do can show where the energy is going. For example, we showed in our recent work that a lot of energy is being transferred into the side chains of the DNA, as opposed to the DNA base pairs. This information is important because in the context of proton beam cancer therapy, for example, you try to induce damage to the DNA side chains, because that damage is very difficult for proteins to repair. If you can induce that side chain damage in a cancer cell, the proteins are less likely to be able to fix that DNA in the cancer cell. You can induce cell death in the cancer cells. That's one example of where a quantum mechanical simulation can provide insights that it probably would be very difficult, if not impossible, to obtain from experiments because the energy transfer happens on the scale of femtoseconds. We can get a resolution of attoseconds in our simulation to understand how the energy is being transferred.

Why are the DNA side chains targeted in this energy transfer?
In DNA, especially when it's under physiological conditions like in water, all of its side chains are missing hydrogen, missing protons. That means those side chains have exposed electrons. These electrons appear to be responsible for this high degree of energy transfer. We have also studied DNA by itself, in a vacuum. But DNA in a vacuum is protonated; you don't have those exposed electrons on the side chains. Only when we studied DNA in water, like when it's under physiological conditions, did we have these exposed electrons. Then we realized that that's important in terms of absorbing energy from these high-energy protons. But it's experimentally difficult to study the DNA under physiological conditions when responding to the proton beam. Even when you go to simulating DNA in water, you have more than 10,000 electrons to simulate, and that's a very challenging task.

"When you simulate DNA in water, you have more than 10,000 electrons to simulate, and that's a very challenging task."

Do you think that these simulations will assist in finding a more efficient way of targeting cancer DNA?
If you really want to improve ion beam therapy, you need to understand how it works. We're doing fundamental science to provide an understanding at the molecular level of how it actually works. Many people talk about things like going beyond protons in terms of the ion beams, things like using carbon ions for example. The rationale is that if you have a carbon ion, it has more charge, so you can deposit a larger amount of energy into the DNA of the cancer cell. That makes sense. A proton has a plus one charge. Carbon, if you strip away all the electrons, is plus six. But does anything else change? Those are the insights that our simulation can provide. Now we have an original simulation with other ions, to show how that behavior of energy transfer changes when you go to things like alpha particles and carbon ions. That can guide people's thinking about improving or advancing the ion beam therapy beyond proton beams.

The simple rationale is, okay, you have more charge, so you can have more energy transfer. There's a simple formula for this. But this is a very idealistic, simplistic idea. If you actually perform a simulation like we do, we can see the degree of ionization for these particles. The carbon is never really carbon plus six. Even with the protons, a proton is never completely a plus one charge. These quantum mechanical simulations can provide those insights into what actually are the charge states of these ions.

What is the importance of focusing in on the fundamental science?
It's easy to appreciate the part of our research that can connect to everyday life, like cancer therapy, for example. But the reason we can perform these calculations and provide these important insights for, in this case, cancer therapy is because there's a lot of fundamental work that goes in before we can perform these simulations. We spend a significant amount of our time developing computer simulation methodologies. It involves a lot of mathematics and a lot of programming. It's not just because we have a supercomputer that we have these simulations. We do need the supercomputer, but we also have to have the computational methods development: a lot of programming, a lot of solving equations, a lot of mathematical derivation. That also has to be done before this simulation can be performed. It's the work that people don't see or read about very often. But still, it's very important.

How are these computational derivations created?
In order for us to do these simulations, we have to create a computer program. To do that, you first have to understand how quantum mechanics works, and also you have to formulate the equations of quantum mechanics in such a way that they can be programmed. Supercomputers come with many processors working in parallel, and computational scientists like us have to program these equations so that the computer program we write can take advantage of all the processors simultaneously. If you want to do this type of work, you don't just need to know math, physics, and chemistry. You also have to learn the computer science and programming aspect. I'm in quantum chemistry, but if you look closely at what's happening in the research, you see a lot of math, physics, chemistry, and computer science. It's quite interdisciplinary. ■

Sigma Xi Congratulates the 2022 cohort of Sigma Xi Fellows



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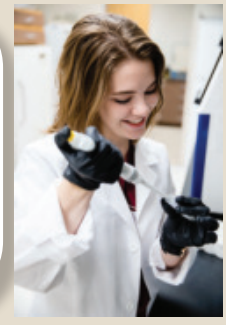
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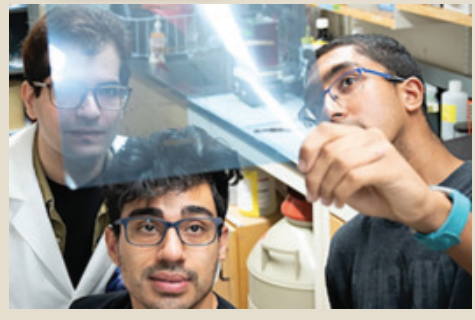
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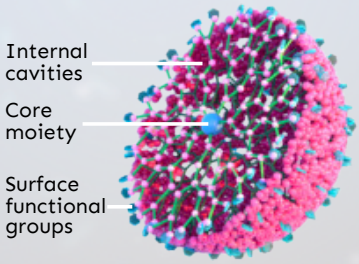
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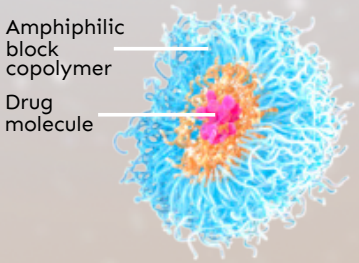
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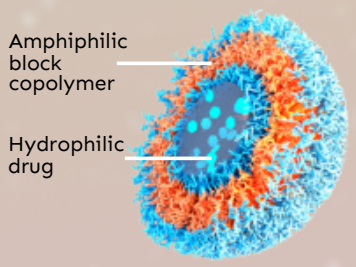
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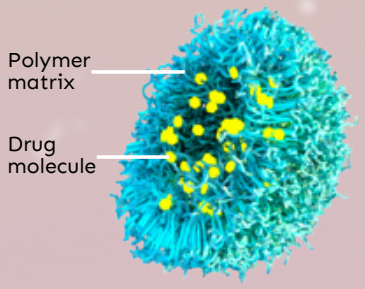
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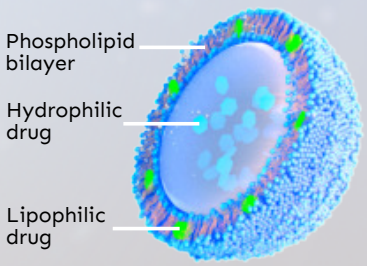


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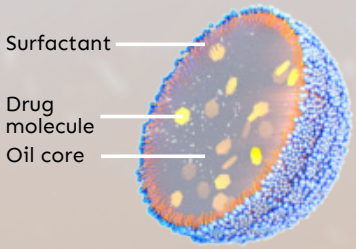


Lipid-based

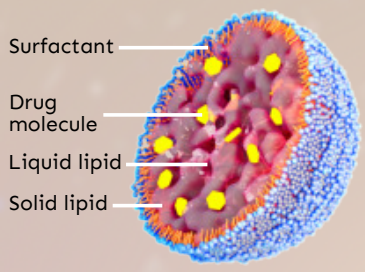
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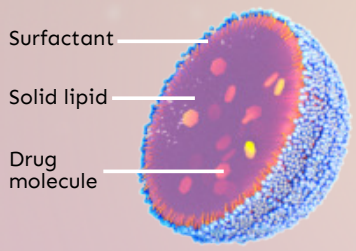
Emulsion



Nanostructured Lipid Carrier

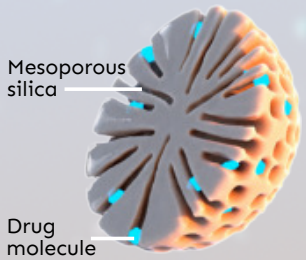


Solid Lipid Nanoparticle

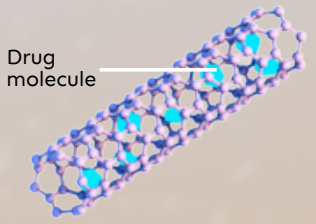


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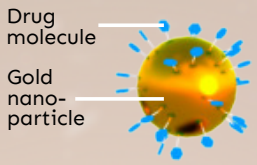
Silica Nanoparticle

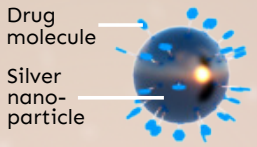


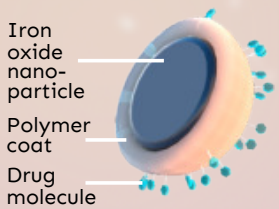
Carbon Nanotube



Metallic Nanoparticles







Nanoclustering Scientific Illustration

In this roundup, managing editor Stacey Lutkoski summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/index.jsp

Hidden Asteroids

Researchers have discovered three near-Earth objects that had been obscured from view by the Sun's glare. Two of these asteroids maintain orbits interior to that of the Earth. The third asteroid, 2022 AP7, crosses Earth's orbit and is about 1.5 kilometers wide, making it the largest potentially hazardous asteroid identified in the past eight years. Although most asteroids circle the Sun in the belt between Mars and Jupiter, there is another group of the space rocks within the orbits of Earth and Venus. Despite being relatively close to Earth, astronomers have found it difficult to detect these objects because of the Sun's glare. An international team used the Dark Energy Camera in Chile to survey the sky at twilight, when there is less glare and fewer atmospheric distortions. Their discovery of the three asteroids highlights how difficult it is to complete a comprehensive survey of asteroids from Earth. NASA plans to launch the Near-Earth Object Surveyor infrared space telescope in 2026, which is designed to identify potentially hazardous asteroids and comets, but the mission has already been postponed several times. It is unlikely that 2022 AP7 will strike Earth, but if a threat did seem imminent, the success of NASA's recent Double Asteroid Redirection Test (DART) probe should ease concerns of a planet-ending impact. (*See infographic, May–June 2021.*) On September 26, 2022, DART slammed into a small asteroid called Diomorphos and successfully shortened its orbit by 32 minutes.

Sheppard, S. S., et al. A deep and wide twilight survey for asteroids interior to Earth and Venus. The Astronomical Journal *164:168 (September 29, 2022).*

Shark-Eye View of Seagrass

Cameras mounted to the dorsal fins of tiger sharks have helped researchers identify the world's largest seagrass ecosystem. Underwater vegetation plays a vital role in marine health, including supporting biodiversity and contributing to carbon sequestration, but monitoring these ecosystems is challenging. Enter, the shark-cam. A group of oceanographers, biologists, and cinema scientists studying seagrass in the Bahamas have developed a camera that can attach to the dorsal fin of tiger sharks (*Galeocerdo cuvier*) using biodegradable cable ties and a dissolvable swivel. The researchers can then observe the shark's environment for 6 to 24 hours, depending on the type of swivel used, before the camera detaches from the shark



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and floats to the surface for retrieval. Remote sensing technologies are unreliable at identifying whether vegetation is seagrass, phytoplankton, or macroalgae. Tiger sharks spend much of their time in seagrass and traverse wide areas as they hunt, making them ideal underwater observers of the ecosystem. Data from the shark-cams combined with other sensing methods indicate that the seagrass habitat covers between 66,000 and 92,000 square kilometers across the Bahama Banks. The success of the animal-based cameras could be applied to other ecosystems that are difficult for humans to access.

Gallagher, A. J., et al. Tiger sharks support the characterization of the world's largest seagrass ecosystem. Nature Communications *13:6328 (November 1, 2022).*

Lab-Grown Neurons Play Pong

Brain cells grown from human stem cells and from mouse embryos can sense and respond to their environment—and even play a video game. A team combining researchers in neuroscience, biomedical engineering, and artificial intelligence used living neurons to create a synthetic biological intelligence system that they call *DishBrain*. This minibrain was connected via electrodes to a video game similar to the classic Atari arcade game *Pong*. The electrodes provided feedback in the form of electrical stimulation to the cells that indicated the location of the ball in relation to the paddle and responded to the cells' decisions. DishBrain appeared to learn the game in about five minutes, demonstrating the ability to self-organize and to display goal-directed behavior in response to its environment. Brain organoids like DishBrain have the potential to help researchers understand the workings of the brain and develop treatments for neurological disorders. (*See "Minibrains: What's in a Name," July–August 2021.*)

Kagan, B. J., et al. In vitro *neurons learn and exhibit sentience when embodied in a simulated game-world.* Neuron *doi:10.1016/j.neuron.2022.09.001 (October 12, 2022).*

Arctic Snow-Paws

A comparative study of bear feet has confirmed what researchers have long suspected: Polar bears' unusually rough pads help them navigate icy terrain. A team led by polymer scientist Ali Dhinojwala of the University of Akron compared the paws of four bear species: polar bears, brown bears, American black bears, and sun bears. They found that polar bear feet have more fur and smaller paw pads than the feet of other bears, but that *papillae* (microscopic



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bumps) on the pads were as much as 1.5 times longer than those of the other species (sun bear paws do not have papillae at all). Friction experiments with three-dimensional models demonstrated that tall papillae increase the surface area in contact with the ground, creating more traction on slippery surfaces. The extra-sticky paw pads help to compensate for their smaller size, which is necessary to minimize heat loss through their feet. Similar comparative studies could help researchers understand how other animal features make them uniquely suited to their environments.

Orndorf, N., A. M. Garner, and A. Dhinojwala. Polar bear paw pad surface roughness and its relevance to contact mechanics on snow. Interface *19:20220466 (November 2, 2022).*

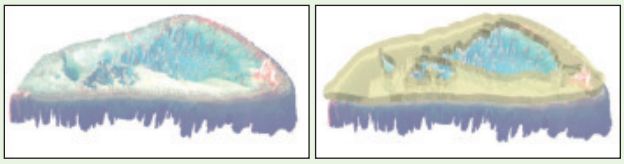
Reef Health from Space

Satellite imaging of sediment formations could be a proxy for coral productivity in a changing climate.

The Great Barrier Reef in Australia is a beautiful place for scientists to visit, but field studies cannot be conducted frequently enough to provide the extensive data needed to monitor coral reefs for signs of stress from climate change. So geoscientist Ana Vila-Concejo of the University of Sydney and her colleagues turned to satellite imagery to see if they could establish any visual measurements that correlated to coral reef health over time. They focused in on what are called *sand aprons*, formations caused by waves pushing sediment into lagoons at the centers of coral reefs.

Healthy coral reefs produce carbonate, the mineral that builds up the coral and the shells of other tiny organisms living on the reef. Carbonate is broken down by waves, or sometimes digested by some fish, to become sand. Waves that wash over the reef carry this sand into the central lagoon, creating a formation that stretches into the apron-like shape. The extent of the sand apron, and its growth over time, therefore relates back to how much carbonate the reef forms, which is an indication of how productive and healthy it is, Vila-Concejo says. "Basically, a coral reef is typically like a bucket; it has a hole inside and tends to trap sediment in there. So the water flow tends to accelerate over the reef and picks up all of this carbonate produced, and moves it," she explains. "As it hits the deeper water, the flow decelerates and drops whatever it is carrying. So the paradigm is that these buckets will fill in over time, but the story is not just as simple as that. It depends how much waves, water, and sediment you have. Not all reefs will infill."

To measure reef sand aprons, Vila-Concejo and her colleagues had to do far more than just look at satellite images. The team started with images of a chain of 21 coral reefs in Capricorn-Bunker Group on the southern end of the Great Barrier Reef (*see opposite page; background image shows part of the sand apron of One Tree Reef*). They combined these images with extensive data from previous fieldwork studies their team had done at these reef sites to map the seafloor, creating what's called a *digital bathymetric model* (*as shown in the left-hand image above for One Tree Reef*). The team then manually digitally outlined the contours of the sand aprons of each of the reefs in this study. Combining these two models gave them a visual estimate of the sand apron infill area and volume for each reef (*as shown in the right-hand image above for One Tree Reef*).



Geocoastal Research Group, School of Geosciences, University of Sydney

As the team reported in the October 11, 2022, issue of the journal *Geology*, they estimate that the Capricorn-Bunker Group produces between 1.8 and 2.66 kilograms of carbonate per square meter per year, or about 659,000 metric tons per year across all 21 reefs. The individual reefs varied widely in their carbonate production, ranging from less than 0.5 kilograms per square meter per year, to 2.83 kilograms per square meter per year. Larger reefs, they found, were typically less filled in, and larger tidal ranges at certain locations may also affect the rate of sediment transport. Local structures, such as the width of the reef flat or the presence of tidal channels, can also be a factor.

Taking One Tree Reef as an example shows the data's complexity. Vila-Concejo has data from a 2009 tropical cyclone that shows that the sand apron at One Tree Reef wasn't extended even by that extreme event, indicating that the maximum sediment transport distance for the reef has already been reached. There is also some conflicting geological evidence, Vila-Concejo says, that about a half-meter sea level drop occurred about 4,000 years ago for unknown reasons, cutting off the reef from ocean sedimentary processes. Accounting for all these factors, the team was still able to calculate historical carbonate productivity for the reefs from when they formed about 8,000 years ago to about 4,000 years ago. For One Tree Reef, they estimated its historical productivity to be about 4.72 kilograms per square meter per year, or about twice the present-day average.

The team's results suggest that reef production may already be suppressed by climate change, even though this formation is currently reasonably healthy. "Over the next 20 or 50 years with sea level rise, the transport capacity will be increased, but will we have enough sediment for those waves to move, because of the health of the reef?" Vila-Concejo asks. "Satellite imagery is helping us scale up our findings. We still need to go to the field and do ground-truthing, but satellite helps us have a longer, more continuous record spread over larger areas." —*Fenella Saunders*

Satellite Images of Coral Reefs

A. Location of the Capricorn-Bunker Group at the southern end of the Great Barrier Reef.

B. North

C. Broomfield

D. Tryon

E. North West

F. Wilson

G. Wreck

H. Heron

I. Sykes

J. Wistari

K. Erskine

L. One Tree

M. Masthead

N. Polmaise

O. Lamont

P. Fitzroy

Q. Llewellyn

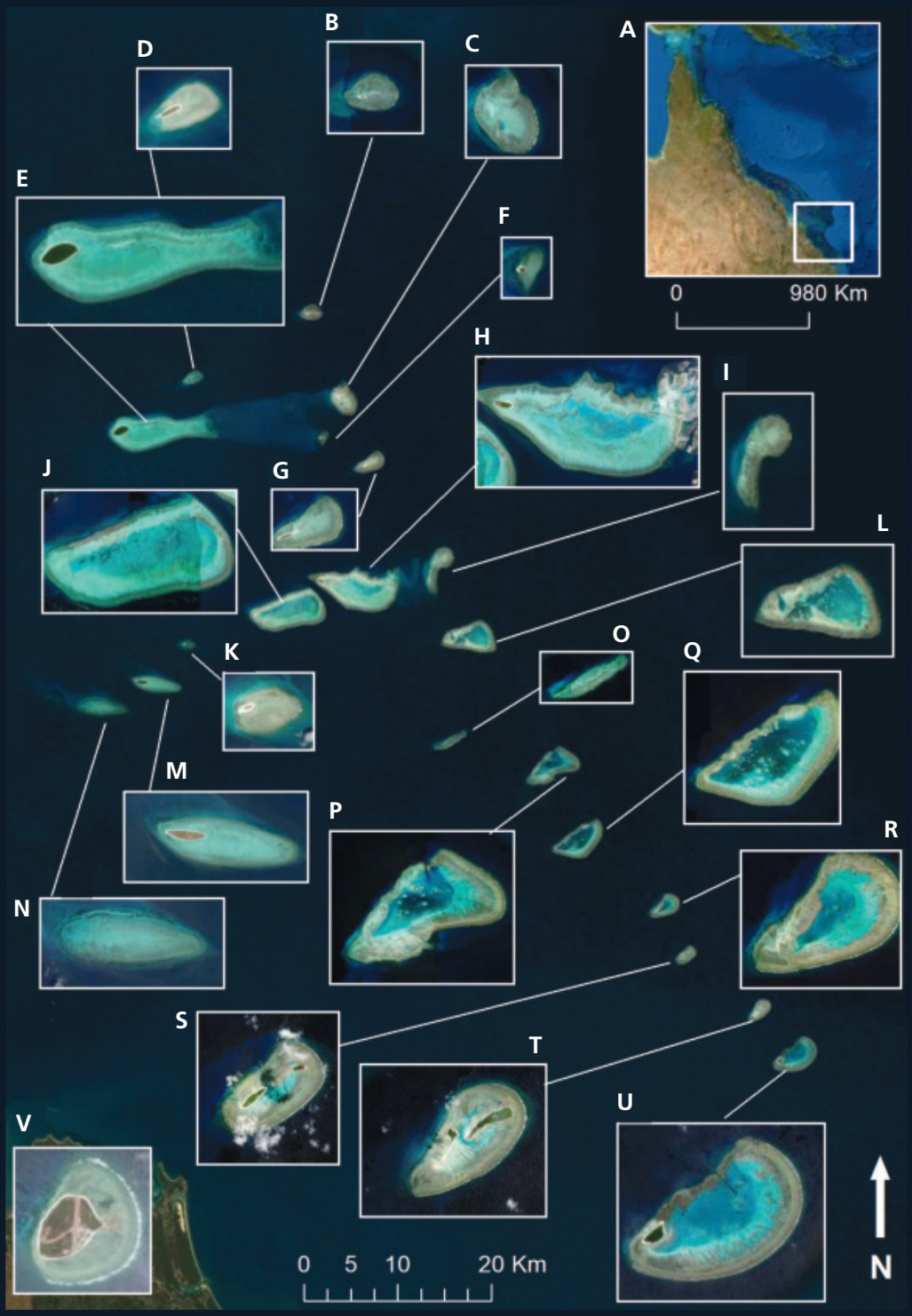
R. Boult

S. Hoskyn

T. Fairfax

U. Lady Musgrave

V. Lady Elliot (73 kilometers farther south)



Geological Society of America; background photo by Amaia Ruiz de Alegria-Arzaburu

A New Picture of Dinosaur Nesting Ecology

From colorful eggs to Arctic babies, a flurry of recent discoveries is providing unprecedented insights into dinosaur reproduction.

Daniel T. Ksepka

A long-standing mystery in paleontology is why we have discovered thousands of eggs from some types of dinosaurs, such as the duck-billed hadrosaurs, but none at all from other types of dinosaurs, such as the armored stegosaurs. For more than a century, most paleontologists hypothesized that all dinosaurs laid hard-shelled eggs. This assumption seemed like a safe one because the closest living relatives of dinosaurs, crocodilians and birds, also lay hard-shelled eggs. In 2020, however, that assumption was completely overturned, opening an exciting new realm of research on dinosaur reproduction.

That revelation—that some dinosaurs laid soft-shelled eggs—and other recent discoveries about dinosaur nests offer vivid glimpses into the lives of long-dead dinosaurs, from egg to parenthood, and show the complicated ways that dinosaurs both resembled and differed from their modern relatives. Narratives about dinosaur research are often framed in the context of new discoveries revealing more and more birdlike anatomy and behaviors. In the case of dinosaur reproduction, the true story is much blurrier.

The Case of the Missing Eggs

The road to our current understanding of dinosaur nesting began long ago. When the first species of dinosaur, *Megalosaurus bucklandi*, was named in 1821, paleontologists knew almost nothing about how dinosaurs reproduced. In 1921, the first major clue emerged: Acclaimed fossil hunter Roy Chapman Andrews discovered intact dinosaur nests in Mongolia. In fact, dinosaur eggs had already been found in France in 1859, but were mistakenly thought to belong to giant birds at the time.

Studying the beautiful elongated oval eggs, Andrews concluded the small ceratopsian dinosaur *Protoceratops* must have laid them. A relative of much larger horned ceratopsians such as *Triceratops*, *Protoceratops* was far and away the most common dinosaur around the excavation site, so it seemed likely the nests belonged to that group. When a skeleton of an unusual beaked theropod dinosaur was found next to one nest, Andrews assumed that it had died pilfering *Protoceratops* eggs. This unusual dinosaur was dubbed *Oviraptor*, meaning "egg thief." For the next 70 years, *Oviraptor* stood falsely accused of stealing eggs.

Then in 1993, a team led by Mark Norell of the American Museum of Natural History returned to Andrew's old fossil hunting grounds and uncovered a truly remarkable skeleton of *Citipati*, a close cousin of *Oviraptor*, brooding a clutch of elongated eggs. The alleged *Protoceratops* eggs turned out to have belonged to oviraptorid theropods the whole time, and the formerly unpopular *Oviraptor* was reimagined as a caring parent.

This discovery, however, created a new mystery: If all those eggs belonged to relatively rare oviraptorids, why had we never found a single egg from the much more abundant *Protoceratops*? Almost a century after Andrews's discovery of the misidentified oviraptorid nest, Norell finally uncovered the first real *Protoceratops* eggs. But something about the eggs puzzled him. Well-preserved embryos were curled up in each egg, but the eggs themselves were barely visible, appearing almost like halos encircling the tiny skeletons. Norell invited molecular paleontology expert Jasmina Wiemann, now at the University of Chicago, to study the chemical structure of the *Protoceratops* eggs.

In 2020, they found that the eggs originally had soft, nonmineralized shells similar to most modern turtle eggs. Parts of the soft eggshell had become phosphatized after burial in the sediment, preserving them from destruction and resulting in the halolike appearance. This discovery explained the mystery of the missing *Protoceratops* eggs: Soft-shelled eggs were very unlikely to be preserved in the fossil record in most circumstances.

All of a sudden, it was clear why the fossilized eggs of some types of dino-

QUICK TAKE

Paleontologists have begun to answer previously elusive questions about life in the Mesozoic: how dinosaurs nested, how eggs matured, and how parents cared for their offspring.

Discoveries about dinosaurs are often framed as revealing more and more birdlike features. Dinosaur reproduction does not fit this frame, with its mix of reptilian and avian traits.

Dinosaur nests evolved from an ancestral state of soft-shelled eggs buried underground to hard, sometimes colorful eggs incubated in partially open nests. Parental care varied.



Andrey Atuchin



© AMNH/M. Ellison

***Protoceratops*, a relative of the much larger *Triceratops*, lived in Asia about 71 to 75 million years ago. Despite the abundance of *Protoceratops* fossils at sites such as the one in the Gobi Desert that Roy Chapman Andrews explored in the 1920s, paleontologists did not find a single egg from this group for about a century. It turns out that a hatchling of *Protoceratops* (*right*), is more likely to show up in the fossil record than the soft-shelled eggs it hatched from (*on following page*). Fossils from this group also indicate that its parents were attentive to nests and hatchlings, unlike modern-day animals with soft-shelled eggs, such as sea turtles.**

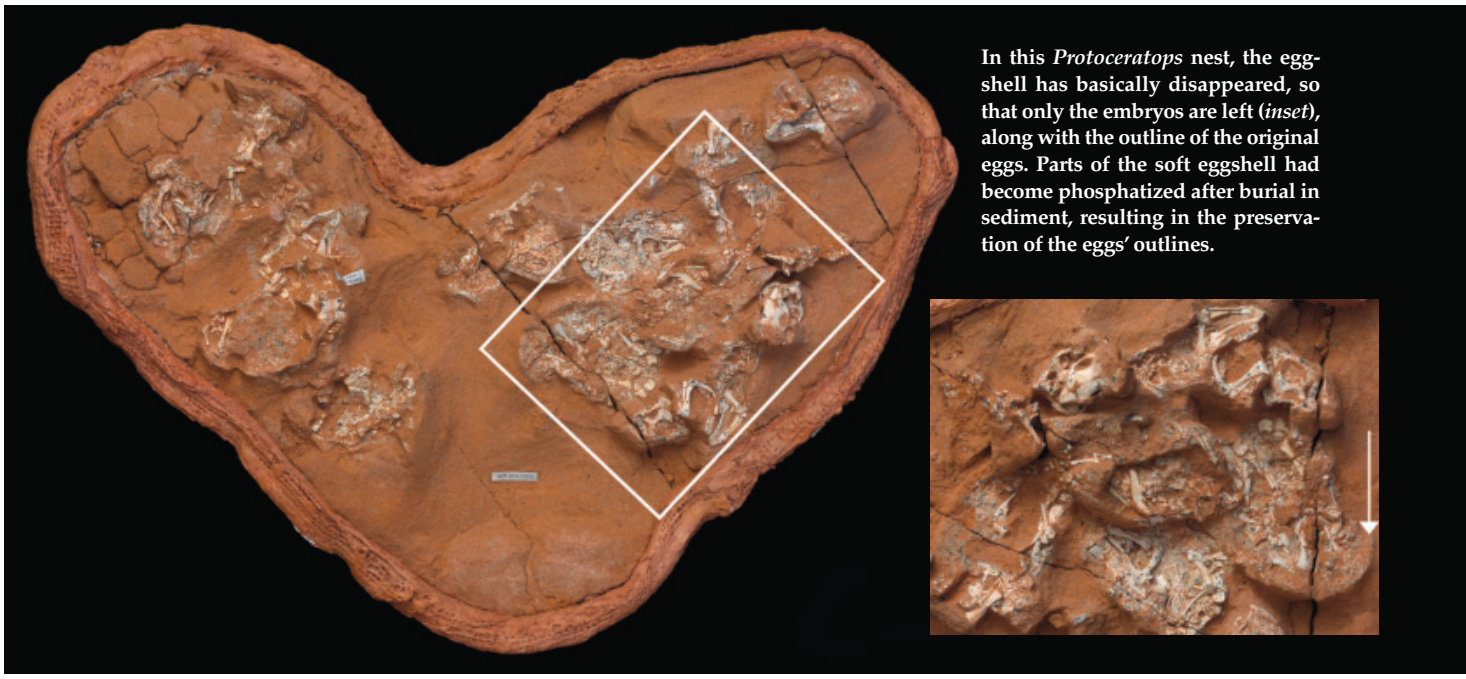
saurs were common, but no eggs at all had been discovered for other types of dinosaurs. Hadrosaurs, sauropods, and many theropods laid eggs with hard, calcite-rich shells. The calcite portion of a hard-shelled egg is essentially "prefossilized" since the mineral calcite can remain stable for hundreds of millions of years. By contrast, the organic components of soft eggshell degrade quickly under most conditions. Hence, an *Oviraptor* egg had a much better chance of showing up in the fossil record than a *Protoceratops* egg.

People are never going to see a live nonavian dinosaur, but thanks to discoveries like these we are now learning previously unimaginable details about dinosaur family life. Dinosaurs were remarkable creatures. Although we tend to emphasize the shared features of dinosaurs and birds, dinosaurs in fact possessed a mixture of birdlike traits, reptilian traits, and unique traits not seen in either group. In the case of *Protoceratops*, finding out that its eggs were soft was completely unexpected since both birds and crocodilians lay hard-shelled eggs. This discovery also unlocked new details of *Protoceratops* nesting behavior. Soft-shelled eggs are more sensitive to the environment, because they lose moisture easily in dry conditions. In addition, parents could not sit directly on top of them without risking a crushed shell. Given these limitations, *Protoceratops* likely buried its eggs in moist sediment and left them to be incubated by external heat sources such as decaying plants or sunlight.

As Norell and Wiemann studied more eggs from species on different branches of the dinosaur family tree, a startling implication emerged: The very first dinosaur egg was probably soft as well. Norell and Wiemann observed that soft eggs were laid by the ancestors of the giant long-necked sauropod dinosaurs, as well as by the winged pterosaurs, which are considered by most paleontologists to be close relatives of dinosaurs. This finding suggests that the earliest dinosaurs were limited to moist nesting environments. Other groups of dinosaurs evolved a hard calcite shell that locked in moisture and allowed them to nest in a wider range of environments. This development would have offered a major advantage, and at least three separate dinosaur lineages evolved hard-shelled eggs independently: theropods, sauropods, and hadrosaurs.

Colorful Clutches

Hard-shelled dinosaur eggs also have impressive stories to tell, revealing the complex diversity of reproductive biology and behaviors among dinosaurs. Today's bird eggs have a remarkable array of patterns. Sandpipers lay eggs with exuberant spots and swirls reminiscent of a Jackson Pollock painting. Robins lay baby blue eggs the same



In this *Protoceratops* nest, the eggshell has basically disappeared, so that only the embryos are left (*inset*), along with the outline of the original eggs. Parts of the soft eggshell had become phosphatized after burial in sediment, resulting in the preservation of the eggs' outlines.

© AMNH/M. Ellison

shade as the sky on a pleasant spring day. The brilliant lacquered green eggs of the elegant crested tinamou look almost ceramic. By contrast, crocodilians lay plain, unpatterned eggs. Colorful eggs make no difference in buried nests, where they can't be seen. But for birds that lay eggs in open nests, color can camouflage the clutch from predators or differentiate parents' eggs from those of other species. For much of the field's history, paleontologists had no way of knowing whether dinosaur eggs shared the plain egg palette of crocodilians or the more colorful palette of bird eggs. Then, Wiemann discovered that secret traces of color were locked deep in the dozens of blanched and stained fossil eggs in museum drawers, awaiting the day scientists figured out how to unlock them.

Using mass spectroscopy, Wiemann identified pigments called *protoporphyrin* and *biliverdin* in the eggs of oviraptorids and other dinosaurs. These two versatile pigments combine in different ways to make up the palette of colors found in modern bird eggs. Examining chemical signatures in layers of eggshell, Wiemann reconstructed the color patterns of dozens of dinosaur eggs. Her work yielded startling results that showed that dinosaur egg morphology and nesting behavior had diversified prolifically from the simple buried nests full of plain, soft-shelled eggs that *Protoceratops* had left behind.

The oviraptorid *Heyuannia* and the famous sickle-clawed dromaeosaur *Deinonychus* turned out to have laid colorful blue-green eggs. Some troodontid eggs that Wiemann tested were found to have been brown, while others were white with speckled or spotted patterns. By contrast, all non-theropod dinosaurs seem to have lacked eggshell pigments. The study's reconstructions of sauropod and hadrosaur eggs showed their color was plain white.

At least three separate dinosaur lineages evolved hard-shelled eggs independently.

The fact that eggshell pigments are detected only in theropods provides another piece of evidence (in addition to features like feathers and a wishbone) that this group of dinosaurs gave rise to modern birds. Birds are the only living amniotes that lay colored eggs, making it likely that eggshell pigments evolved a single time in an ancestor of birds and advanced theropods.

Fossil egg color also holds clues to nesting behaviors. The evolutionary journey from the simple nest of an early dinosaur (essentially a hole scooped in soil) to the meticulously constructed nests of modern birds such as weaver finches is a long one. Oviraptorids represent the first big step—they differed from earlier dinosaurs in leaving their eggs partially exposed in a shallow excavation scraped into the ground.

The spectacular nesting *Citipati* fossil mentioned earlier provides some of the most remarkable evidence of how these dinosaurs incubated their eggs. The large adult skeleton is preserved at the center of a ring of eggs, with its arms wrapped around the precious clutch. This *Citipati* parent was shielding the eggs when it perished in a sandstorm. But, the eggs are widely spaced, and it appears the adult avoided sitting directly on top of them, possibly to prevent crushing them. Oviraptorids like *Citipati* seem to have covered their nests with their feathered arms to insulate them, but avoided direct body contact.

Troodontids, which occupy a branch closer to birds on the evolutionary tree, developed even more advanced nesting strategies. Troodontid nests from North America show an arrangement with the eggs closer to the center. This would allow the brooding parent to cover the entire clutch directly with its belly, warming the eggs using a behavior known as *contact incubation* just as most modern birds do.

The new incubation strategies explored by oviraptorids and troodontids required the eggs to be partially exposed at the surface, leaving them visible for the first time in dinosaur evolution. The appearance of colored eggs coincides with the evolution of

these partially open nests, and so may have been driven by new selective pressures. Brown speckled eggs, for example, may have been better camouflaged from predators when the parents left the nest to feed.

The advantage of baby blue eggs is a bit more uncertain. Some modern birds use egg colors to help fight brood parasites such as cuckoos, by making any imposter eggs more obvious so that they can be discarded by the parents. For now, we can only speculate as to the existence of dinosaur brood parasites, but the idea of a furtive oviraptorid sneaking an egg into another dinosaur's nest is satisfying to ponder. (*See the 2022 digital feature "Putting Eggs in Many Baskets": amsci.org/node/4891)*

Fossil Egg Timers

With the discovery of more dinosaur eggs and embryos, paleontologists can start to reconstruct what was happening while those eggs sat in nests millions of years ago. Higher incubation temperatures speed up embryonic development, which shortens the length of time when eggs are vulnerable. Birds are masters of speeding up hatching, using their body heat and rotating their eggs in the nest to usher their hatchlings into the world more quickly. Accounting for body size (larger eggs take longer to incubate), birds complete egg incubation roughly twice as fast as crocodilians. For a long time, paleontologists lacked a reliable way to determine whether dinosaurs had long incubation times like crocodiles or short incubation times like birds.

A cutting-edge idea recently unlocked a hidden timestamp on dinosaur embryos. As teeth grow, cells called *odontoblasts* inject a tiny sliver of dentin below the outer enamel layer each night. The dentine hardens overnight, forming a ring called a *von Ebner line*. The number of these lines thus indicates the age of a tooth. For adult dinosaurs, von Ebner lines can reveal how quickly teeth were replaced. But for embryonic dinosaurs, they can reveal the age of the embryo itself. Like crocodiles, dinosaurs began growing their teeth while still inside the egg. So, counting up the von Ebner lines in the teeth of nearly hatched dinosaur embryos—and adding a little extra time to account for the fact that teeth usually start forming several weeks after the egg is laid—can reveal how many days a fossil embryo had been inside the egg.

Evolution doesn't always align with easy assumptions about early and modern traits.

Greg Erickson of Florida State University had studied von Ebner lines in adult dinosaurs before, and recently he has turned his focus to babies. Thanks to increasingly powerful CT scanners and new fossil embryo discoveries, Erickson's team was able to count von Ebner lines in those precious *Protoceratops* fossils that had revealed the soft-shelled nature of the ancestral dinosaur egg. In 2017, Erickson's tooth scans revealed that the eggs would have hatched approximately 83 days after being laid. Erickson's team found that the giant duck-billed hadrosaur *Hypacrosaurus* took about twice as long to incubate its eggs at 173 days, which follows the general pattern of larger animals having longer incubation times. These plant-eating dinosaurs were thus more similar to crocodilians in their growth patterns than to modern birds.

Using similar methods, another team led by Dave Varricchio of Montana State University found in 2018 that troodontids were a bit faster, with a 74-day incubation time that falls right between the times predicted for a bird or crocodile of the same body size. What about *Oviraptor*? Unfortunately, von Ebner lines cannot help us study this dinosaur, because it had no teeth.

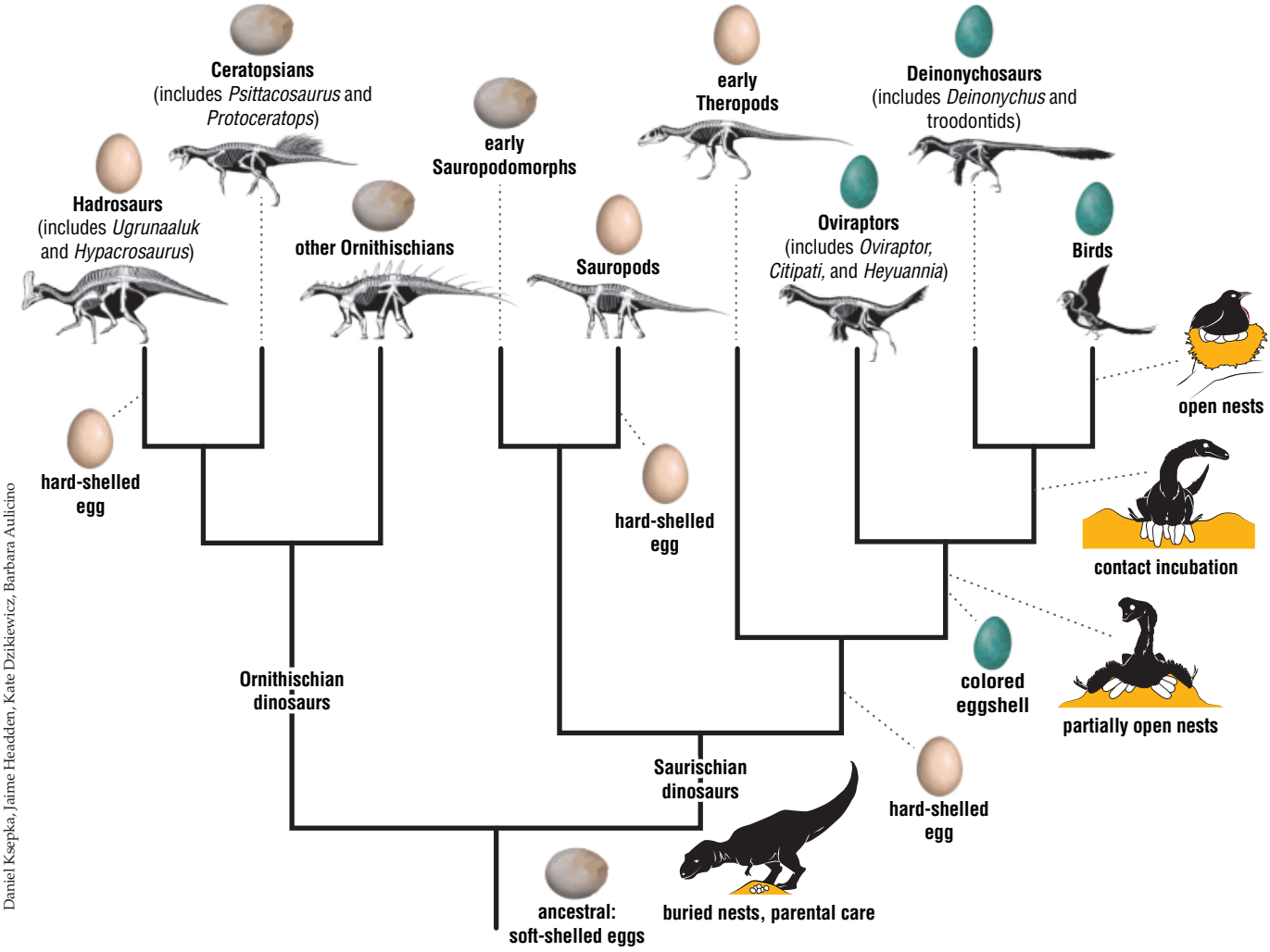


Courtesy of Jasmina Wiemann



Courtesy of Jasmina Wiemann

Today's bird eggs exhibit a remarkable palette of colors and patterns, and recent work shows that dinosaur eggs, such as the one in the bottom right corner (*above*), were varied in color, too. Colorful eggs make no difference in buried nests, where they can't be seen. But for birds that lay eggs in open nests—and the dinosaurs that did so before them—color could camouflage the clutch from predators or differentiate parents' eggs from those of other species. In fossil nests from the oviraptorid *Heyuannia* (*right*), Jasmina Wiemann, now at the University of Chicago, identified pigments in the eggs to determine their original color. The eggs in this nest were originally blue-green.

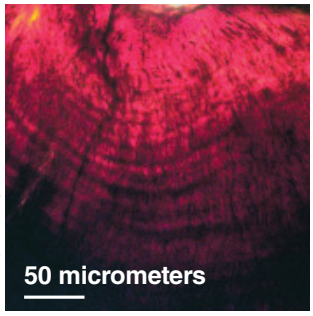


Daniel Ksepka, Jaime Headden, Kate Dzikiewicz, Barbara Aulicino

Recent discoveries about dinosaur nests as well as egg texture and color reveal information about the evolution of dinosaur eggs and nesting behaviors. The common ancestor of all dinosaurs laid soft-shelled eggs buried in moist soil, and hard-shelled eggs evolved multiple times in several lineages. The rise of colored eggs in the fossil record coincides with the shift to partially open nests that dinosaurs incubated by sitting on them, much as many modern birds do.

Dinosaur Day Care?

Even though *Protoceratops* laid soft-shelled eggs in turtle-like nests, it also showed hints of attentive nesting behaviors like modern birds exhibit. This mosaic of traits is part of what makes dinosaurs so interesting and surprising: Evolution doesn't always align with easy assumptions about early and modern traits. David Fastovsky of the University of Rhode Island reported a *Protoceratops* nest that lacked eggs, but contained 15 juveniles tumbled together in a nesting burrow. The young *Protoceratops* were relatively large compared to hatchlings, and so must have been hanging around the nest together for many weeks, rather than scattering to the wind like many modern reptiles do after emerging from the egg.



Courtesy of Greg Erickson

As dinosaur teeth grow, a tiny sliver of dentin is deposited below the enamel layer each night, forming marks called *von Ebner lines*. In images such as this one showing a section of tooth from an embryonic hadrosaur (*Hypacrosaurus stebingeri*), illuminated under a polarized light microscope, paleontologists can count the lines to determine how old the embryo was when it died. (From Erickson, et al., 2017.)

A similar aggregation of babies is also known for *Psittacosaurus*, an earlier relative of *Protoceratops*. In the case of *Psittacosaurus*, a five-year-old subadult was found in a nest burrow with 24 smaller babies. The larger individual was too young to be a parent, and so may have been an older sibling watching over the young.

Parental care becomes even more important in challenging environments, and new discoveries show that some dinosaurs raised their young in extreme conditions. One of the ultimate frontiers in understanding dinosaur nesting is the High Arctic. Back when all dinosaurs were assumed to have ectothermic metabolisms, paleontologists concluded they would not be able to survive high latitude winters. Today, we know many dinosaurs thrived farther north than we ever imagined was possible. During the Cretaceous Period, North America was even closer to the North Pole. Dinosaurs ranged into the northernmost reaches of present-day Alaska, reaching latitudes beyond 80 degrees

north, far above the Arctic Circle (66.33 degrees north).

Since 2009, field teams led by Patrick Druckenmiller of the University of Alaska, Fairbanks, have collected a treasure trove of High Arctic fossils including hadrosaurs, ceratopsians, and troodontids. Even more remarkably, the team discovered bones of juveniles from each of these groups. In many cases, the tiny teeth and bones fit on the head of a pin, indicating that the dinosaurs were truly recent hatchlings, some no bigger than a guinea pig.

During the Cretaceous, northern Alaska would experience more than 80 days of continuous darkness during the winter. Because of this harsh season, paleontologists had proposed that the Arctic dinosaurs enjoyed the sunny summer months but migrated south before the Sun disappeared in October. The discovery of juvenile fossils in Alaska suggests that many species instead stayed put for the polar winter.

Druckenmiller and Erickson teamed up to combine polar daylight models and incubation estimates and concluded there simply wasn't enough time for the polar dinosaurs to undertake a major migration. The Alaskan hadrosaur *Ugrunaaluk* needed to incubate its eggs for nearly six months. Even if this species began nesting at the very start of spring, the calendar left almost no time between hatching and the onset of winter darkness. Druckenmiller's team concluded that its young would have been too tiny to trek the roughly 2,500 kilometers required to get south of the Arctic Circle before the Sun vanished.

Parental care becomes especially important in challenging environments, and some dinosaurs raised their young in extreme conditions.

Combined with the evidence from other hadrosaur species that parents tended to their hatchlings, a remarkable picture emerges: *Ugrunaaluk* herds may have carefully tended their babies through many weeks of polar darkness, helping them forage on "leftover" bark, ferns, and moss under the northern lights. Such a lifestyle may have been possible due to the warmer Cretaceous climate, which would have meant snowy conditions for part of the year but less extreme Arctic temperatures than those that occur today.



Courtesy of Patrick Druckenmiller

During a collection trip in Alaska, a field team led by Patrick Druckenmiller found fossils in the High Arctic, including hadrosaurs, ceratopsians, and troodontids, as well as some from juveniles. Some of the teeth and bones are quite tiny, indicating that they were very recent hatchlings at the time of their deaths. Paleontologists once thought dinosaurs could not have survived so far north, but today it is recognized that many dinosaurs thrived above the Arctic Circle.

Hard Eggs to Crack

The evolution of dinosaur nesting shows the diversity of strategies that arose during the millions of years that these animals walked the Earth. Some recent discoveries emphasize the similarities between theropods and birds, such as colored eggs and evidence of tending nests and young. On the other hand, some dinosaurs were far from avian in their nesting ecology, burying soft-shelled eggs in the ground like sea turtles to incubate on their own over extended periods. One thing is certain—at the rapid pace of research innovation seen over the past few years, we can expect to learn more secrets of how dinosaurs nested and raised their young in the near future.

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Altering an Icon

San Francisco's Golden Gate Bridge has undergone several retrofits for increased stability and safety—sometimes with unintended consequences.

Henry Petroski

Eyal Aharon/Alamy Stock Photo

An underside view of the Golden Gate Bridge shows the bottom horizontal stiffening truss that was added in the early 1950s to prevent the bridge deck from twisting in high winds. However, the added weight on the cables prevented the bridge from later use by trains.

The Golden Gate Bridge might be said to be the West Coast version of the Brooklyn Bridge. They share the basic features of a suspension bridge, most noticeably in the parabolic sag of their main cables that support a shallow arched roadway stiffened by trusses composed of triangles. Yet they do not resemble each other in their more prominent architectural details. The staid Brooklyn is characterized by tall Gothic archways piercing its massive masonry towers, from the top of which radiate its signature diagonal stay cables. The Golden Gate has soaring art deco steel towers that are dominated by crisp horizontal and vertical planes and are painted a bold international orange color.

The Brooklyn Bridge took 14 years to build and opened in 1883; the Golden Gate was under construction for three and a third years and was completed in 1937. Each bridge was record-setting for its time. The total length of the Brooklyn is a tad over 6,000 feet, or about 1.1 miles (1.8 kilometers) from end to end. That of the Golden Gate is just short of 9,000 feet, or about 1.7 miles (2.7 kilometers), in total length, making it about one and a half times as long as the Brooklyn. But the accepted measure of engineering achievement for a suspension bridge is the distance between towers, which for the Brooklyn is within five feet of 1,600 (about 0.5 kilometers) and for the Golden Gate is exactly 4,200 feet (1.3 kilometers), a factor of about two and a third times as long.

Since their respective openings, these bridges have each undergone changes in structure that might be considered by the nonengineer to be so inconsequential in scale as to go unnoticed from a distance. However, each change altered the way the bridge behaved and how it functioned for its users, both vehicular and pedestrian. The original configuration of the Brooklyn Bridge's roadway contained in each direction two narrow lanes for horse-drawn carriage traffic beside a single railroad track, all separated by an elevated walkway for pedestrians. The tracks carried cable-car–like trains that shuttled passengers between terminals built at the foot of the bridge on both the Brooklyn and Manhattan sides. Over time, the trains were replaced by lighter trolley cars and eventually were eliminated to accommodate three lanes of roadway for automobiles and trucks.

The original layout of the bridge deck had vertical stiffening trusses on each side of the railroad tracks. The inside trusses remain in place, but the outside ones were relocated to the edges of the bridge deck to eliminate a barrier between the motor vehicle lanes, but this change did not significantly alter the dead load on the bridge deck or its stiffness. With the continued growth of traffic in volume and in the weight of motor vehicles, trucks were banned

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from the bridge altogether. Also, with the growing encouragement and use of bicycles, which shared the elevated walkway with pedestrians, safety concerns led to a dedicated bike lane.

Sitting Steady

The Golden Gate Bridge has undergone more significant structural and behavioral changes. The bridge was designed at a time when the state-of-the-art in bridge engineering was to make the roadway of a suspension bridge look as slender as possible. This aesthetic imperative worked fine for bridges designed to carry multiple lanes of vehicular traffic in addition to railroad trains and pedestrians. Around large cities, this trend led to bridges with three or four traffic lanes in each direction plus tracks for commuter trains. The resulting wide bridge decks were necessarily heavy, and this feature even in the absence of the stiffening trusses made the roadways very stable in the wind. However, as suspension bridges began also to be built in less populated areas, where traffic consisted almost exclusively of cars and trucks, trussless decks carried only two lanes of traffic plus a very narrow sidewalk or two. This layout naturally meant the decks were lighter, which in turn led them to be more flexible, which in time manifested itself as excessive motion in the wind.

John Roebling, the engineer of the Brooklyn Bridge, understood this problem in the middle of the 19th century, when wind was destroying suspension bridges, and his design imperative for a bridge to sit steady in the wind was that its deck be sufficiently stiff by having substantial weight, longitudinal trusses, and diagonal stay cables. His Brooklyn Bridge epitomized the application of this formula. However, beginning early in the 20th century, suspension bridge design trended toward a sleek aesthetic combined with a narrow structure spanning a greater distance. In other words, the bridge deck became lighter and less stiff and less constrained. As the design of any bridge is basically a theoretical hypothesis until it is built and tested by traffic and the elements, bridges designed and constructed in the 1930s tended to be susceptible to movement in strong winds, an old phenomenon that did not manifest itself anew until the second half of the decade. The Golden Gate Bridge fell into this category.

The bridge was designed and built with a pair of vertical stiffening trusses connected by a horizontal one incorporated into the deck, which carried six traffic lanes and two wide sidewalks. The truss arrangement proved to be inadequate in preventing the roadway from excessive movement. The deck was designed to move almost 30 feet



This photo of the Golden Gate Bridge during construction in the 1930s shows what the underside of the bridge looked like before the bottom horizontal truss was added.

(9 meters) laterally in a crosswind, a distortion that was easily seen by sighting along a line connecting the bridge's two towers. A certain amount of vertical displacement was also expected, but not to the extent that traveling waves were observed to develop along the length of the roadway. When the Tacoma Narrows Bridge was brought down in 1940 by a 40 mile-per-hour (64 kilometer-per-hour) wind that induced vertical and twisting oscillations along its entire length, there was cause for concern, because winds through the Golden Gate strait can gust to 75 miles (121 kilometers) per hour. Strong winds can also cause vehicles on the bridge to become difficult to control, and can blow over trucks with large, exposed side panels. In 1951, wind caused the bridge deck to sway and roll, and there was concern that these motions could become unstable and develop into the kind of twisting that destroyed the Tacoma Narrows Bridge. To address such issues, an additional horizontal truss was added that connected the bottoms of the two vertical ones of the Golden Gate. By closing the trusswork in this way, the bridge deck was made significantly stiffer, especially against being twisted.

Each change in structure altered the way the bridge behaved and how it functioned for its users, both vehicular and pedestrian.

The positive retrofit improved the stability of the roadway, but the additional weight of steel added by augmenting the original trusswork put the dead weight of the deck too close to the limit that the main cables were designed to support. As a result, when there was talk of extending the tracks of the Bay Area Rapid Transit system across the bridge and into Marin County, the plan had to be abandoned. Such can be the kind of unintended negative consequence of making what appears otherwise to be a positive change. It was not the last time a design change authorized by the Golden Gate Bridge, Highway, and Transportation District would come back to bite.

Safety First

In the meantime, another issue with the bridge arose. The dramatic setting of the iconic structure between the roiling of the vast Pacific Ocean to the west and the relative calm of the safe harbor known as San Francisco Bay to the east makes the bridge mark an entranceway of sorts. But the bridge's location is also prone to fog rolling in, engulfing the bridge so thoroughly that little more than the tops of its towers remain visible, as if they were held aloft by nothing but clouds of mist. For whatever reason, the bridge is also the site of choice for suicides. As of last year, more than 1,800 people had climbed over the sidewalk railing and jumped from 220 feet (67 meters) above the water—an average of 20 suicides per year. Hundreds more were prevented each year by the intervention of bridge and highway patrol crews and concerned citizens. A passive physical barrier was believed to be the definitive solution that was needed.

A debate about adding any kind of suicide prevention system to the bridge had raged for decades, but it came to a

From the holdings of the Golden Gate Bridge, Highway, and Transportation District



Yalonda M. James/AP Images

The Suicide Deterrent System, also known as the Safety Net, for the Golden Gate Bridge is scheduled to be completed in 2023. It will be placed 20 feet (6 meters) below the bridge sidewalk and will extend 20 feet (6 meters) out from the bridge, to prevent anyone from easily jumping into the water. Some critics are concerned about the net's effect on the bridge's aesthetics. A full-scale section of the Safety Net will be used to train first responders.

potential resolution in 2014, when the region's Metropolitan Transportation Commission pushed for the funding of a $66 million project to either build a high fence atop the railing or extend a safety net out beyond the edge of the bridge, to be paid for in part by a planned toll increase. (The toll for an automobile would go from $6 to $8, collected only from northbound traffic; the Golden Gate was the first major toll bridge to charge tolls only one way, thereby allowing traffic to flow freely in at least the other direction.) The toll hike was expected to increase revenue by $138 million, which the district had initially planned to use for seismic reinforcement of the bridge, the installation of a moveable barrier to allow the six-lane roadway to be divided unequally during rush hours, and improvements in ferry and bus service. The transportation commission asked the bridge district to divert $12 million of their windfall toward the suicide barrier. Once funding was in place, the project proceeded in earnest.

The so-called Suicide Deterrent Net System, euphemistically referred to as the Safety Net, was designed "to minimize impacts to Bridge views and appearance," according to the bridge district, and to allow the daily operation and maintenance of the bridge to proceed unimpeded. The net was to be positioned 20 feet (6 meters) below the sidewalk and extend out 20 feet (6 meters) from each railing. Woven from stainless-steel rope, the chain-link-fence–like netting would rest on horizontal struts cantilevered out every 50 feet (15 meters) from vertical struts that would be continuations of the vertical members of the bridge's stiffening truss, thereby minimizing visual discontinuity. By painting the safety system parts the same color as the bridge, it was expected to be all but invisible from a distance. But anyone striking the net after jumping or falling that distance is likely to sustain injuries, making it imperative that area first responders be trained in rescuing them. The training will be done at a Marin County fire station tower, where a full-scale mock-up of the net has been constructed.

The new railing design caused an "eerie hum" to emanate from the bridge on windy days, becoming unbearable for residents living even some distance away.

Because the Safety Net will add additional steel and hence additional weight to the already heavily loaded bridge, part of the project involved altering the weight of the railing to compensate. This change was done with a simple railing redesign, which promised not only to compensate somewhat for the added weight of the barrier but also to offer less resistance to the wind. Such a result was clearly desirable, especially because the addition of the suicide barrier was going to add wind-resisting surfaces and so increase the overall wind force on the bridge. It appeared that this addition could be offset by reducing the surface area that the balustrade presented to the wind.

The original railing design was in keeping with the hard edges of the towers: The balusters were steel H-sections attached by rivets to steel channel shapes that constituted the top and bottom members of the balustrade. The 4-inch-wide (10-centimeter-wide) flange of each H-section was oriented parallel to the railing length, giving the impression of a simple fence with pickets spaced 4 inches (10 centimeters) apart. The change consisted of replacing the H-sections with 4-by-¼-inch (10-by-0.6-centimeter) steel plates, with the wider face oriented perpendicular to the length of the railing. By presenting to the wind a face that is only a ¼-inch (0.6 centimeters) wide every 4 inches (10 centimeters), the wind resistance of the balustrade was significantly lowered and so was the force of the wind on the bridge.

In 1993, the railing replacement operation attracted the attention of Richard Bulan, a San Francisco native who had fond memories of the bridge. He imagined salvaging some railing to make a headboard for his bed and asked the contractor replacing 12-foot-long (3.5-meter-long) sections of the railing, each of which weighed of the order of 1,000 pounds (450 kilograms), if he could acquire one. While converting the railing section into a headboard, Bulan got the idea of making other pieces of furniture out of salvaged and refinished railing, which in many places had been deteriorating from exposure to the wind and salt air. Because the contractor's responsibility included carting away the sections of old railing at his own expense, he agreed to let Bulan have all he wanted for his nascent enterprise. His plan was to cut up the rail sections, clean them of paint and rust, and reassemble usable parts into pieces of furniture, such as bookends, lamps, and coffee and end tables, which he now sells as pieces of nostalgia through his Golden Gate Design & Furniture Company.

Look Out for Bicycles

A 2013 study conducted by the Golden Gate Bridge, Highway, and Transportation District determined that the maximum sustained wind speed the original bridge was designed to take was about 70 miles (112 kilometers) per hour. However, at least three times in its history (1951, 1982, and 1983) the bridge has been subjected to gusts near to or exceeding that value, forcing it to be closed to traffic. The new railing design was expected to make the bridge safe in winds up to 100 miles (160 kilometers) per hour. However, as the railing replacement project proceeded, two unanticipated consequences became clear.

One was the development of an "eerie hum"—described as sounding like "chanting monks" and a "wheezing kazoo"—emanating from the bridge on windy days. In 2020 it became unbearable for residents living as far as 3 miles (5 kilometers) away. A study of the phenomenon revealed that the frequency of the sound was about 440 hertz, and it occurred when the wind direction was at a slight angle to the long dimension of the thin slats of the railing. Wind tunnel tests of a full-scale section of railing were conducted to explore ways to quiet the hum.

Meanwhile, during the time when sections of old railing were being replaced by new, cyclists who pedaled regularly across the bridge experienced increased difficulty in maintaining their balance on windier days, especially as they rode past new sections of railing. Whereas the old design had provided somewhat of a barrier against crosswinds, the newer design allowed wind to blow across the sidewalk with much greater velocity. Even experienced bicycle riders reported having difficulty in steering a straight path when traveling at about 8 miles (12 kilometers) per hour, a problem that disappeared as soon as they reached a location where the old railing was still in place.

The Marin County Bicycle Coalition, an advocacy group, challenged the claim that such reports were anecdotal by presenting anemometer readings showing that the velocity of the wind blowing through the new railing could be as much as two or three times what it was through the old. The coalition reminded citizens on its website that "anyone who has ever ridden a bike knows that a 10-mph crosswind pales in comparison to one blowing at 20 or 30 mph." Further confirmation of the problem came from the results of a coalition survey that found that 84 percent of respondents reported that riding across the bridge had become worse since the new railing was installed, and 62 percent claimed it to be "much worse." The coalition also asserted that the survey revealed that the bridge district was "*vastly* underreporting the number of bicycle crashes on the bridge," because nearly 20 percent of respondents had reported having crashed because of the wind.



From the holdings of the Golden Gate Bridge, Highway, and Transportation District

Redesigned railing for the Golden Gate Bridge has been installed to offset the weight and wind force on the bridge, which will be increased by the addition of the Safety Net. However, this balustrade design has elevated the wind force on cyclists on the bridge to a potentially dangerous extent, a result that apparently wasn't considered by the designers.

In response to such revelations, the bridge district stated that the new railing design was the result of "decades of work," some done as early as the 1990s, "to make the bridge able to withstand high winds," evoking the collapse of the Tacoma Narrows Bridge as a warning against not taking action. But whereas the safety of the bridge had been given high priority, it was not clear that the effect on cyclist safety was even taken into account. It remains to be seen what, besides warning cyclists of the wind effect, might be done to mitigate the force of the wind blowing across the sidewalk.

Furthermore, the humming sound was not anticipated to be as loud as it proved to be. In 2010, the final environmental impact report for the bridge modification project stated that the changes would not cause any substantial change in ambient noise. However, once in place, the sound emanating from the new railing arrangement was found to reach 100 decibels. When wind tunnel tests indicated that the noise could be reduced by 75 percent by installing thin, U-shaped clips made of aluminum with rubber inserts over the windward face of the slats, a $450,000 retrofit of the retrofit was approved. The job was supposed to be completed late last year but remains ongoing.

There has also been a delay—and a cost increase—for the installation of the suicide barrier. Contractor bids for the job came in at about double the estimated $76 million cost, which by September 2022 had risen to about $222 million. The metal netting began to be installed last year, and the barrier is expected to be completed this November. Those who have worked so hard to achieve the goal of a safer and quieter bridge have little choice but to remain patiently hopeful that it will be.

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Writing to Facilitate Reading

Supplying full grammatical closure to main clauses makes a significant difference in reader comprehension.

George D. Gopen

In the past decade, I have examined the writing of several thousand scientists. So far, none have been free of a malady that I call the *main clause first problem.*

In the November–December 2022 issue of *American Scientist*, I explored the nature of the *stress position*. A stress position occurs whenever the grammatical structure of a sentence comes to a full halt. The syntactic closure provided by these marks of punctuation invites a reader to read the last words with additional emphasis. Yet most of us place the most stress-worthy information elsewhere in the sentence, forcing our readers to guess for themselves which words to emphasize.

The main clause first problem that I deal with here is a subcategory of the larger stress position problem. Simply stated, it occurs when a main clause ends with none of the punctuation marks that can produce a stress position—a colon, semicolon, or period.

A *unit of discourse* is any group of consecutive words that has a beginning and an end. Of the many units we were taught in grammar classes, there are only three that influence how readers understand writing.

The first and most important of these is the *main clause*. It contains a subject and a verb; it can stand by itself as a complete sentence.

The second is referred to as the *dependent clause*; but in context, it makes more sense to call it the *qualifying clause*. It covers all clauses that do not rise to the level of a main clause because, despite having a subject and a verb, it cannot stand as a sentence by itself. This disqualification is usually caused by it beginning with a word such as "if," "since," "that," "which," or "although." The job of these clauses is not to "depend" on the main clause but rather to "qualify" it.

When a main clause ends with none of the punctuation marks that can produce a stress position, it forces readers to guess for themselves which words to emphasize.

The third unit of discourse we must keep in mind is a *phrase*. It does not rise to the level of a clause because it lacks a subject and verb.

We need to be able to recognize these three units of discourse because, by their very nature, they send instructions to our readers as to how much weight should be given to the information located there.

The main clause says, "I am so whole and so important that I could stand by myself as a sentence. I therefore contain something of importance. *Stress something in me*."

The qualifying clause says, "Although I contain both a subject and a verb, and therefore carry some weight and dignity, my sole purpose here is to help modify or support or qualify my more important sibling, the main clause. *Do not stress anything in me*."

The phrase says, "I am just some extra information you should know. *Do not stress me*."

It is essential that these instructions do not conflict with the instructions sent by the presence or lack of a stress position. If you put stress-worthy material in either a qualifying clause or a phrase, both of which say "don't stress me," you confuse your reader. The material in question may sound stress-worthy, but the unit of discourse it inhabits instructs the reader not to stress it.

If you put stress-worthy material in a main clause, but supply for it no stress position, you also confuse your reader: The main clause invites the reader to stress something in it; but its lack of a stress position tells the reader not to stress anything. This conundrum is the constantly recurring problem in scientific writing that I am calling the *main clause first problem*.

The result of this main clause first conflict is confusion for the reader.

QUICK TAKE

Scientist writers need to understand the parts of a sentence and how they cue the reader to make decisions about what words or ideas are the most important.

Pairing the correct parts of a sentence, called *units of discourse*, with the appropriate punctuation, will give readers clear and nonconflicting instructions on what to stress.

Writing with attention to these sentence elements can both clarify the writer's intentions and reduce the amount of effort required from readers.



Acquired by Henry Walters with the Massarenti Collection, 1902

Allegory of Grammar **by Laurent de La Hyre (1606–1656) depicts grammar as a woman holding a Latin scroll that translates as "A meaningful and literate word spoken in the correct manner." Her watering plants is a symbol for how understanding grammar can encourage young minds to grow. Similarly, understanding the role of clauses and punctuation in cueing reader emphasis can lead to better comprehension.**

That confusion—especially because it happens so often—can mislead your readers in their efforts to grasp your meaning. It will also tire them out.

Whenever you end a main clause with a comma (which is incapable of producing a stress position) or with no punctuation whatever, you are leaving it up to your readers to make the important decisions about emphasis that you should have been making for them. There they are, in the middle of your sentence, with some portion of their mind needing to reflect backward, trying to decide whether or not they should have stressed something, and, if so, what. But most of their mind is hurtling forward to finish the job of reading your sentence. You have essentially made them into your coauthors.

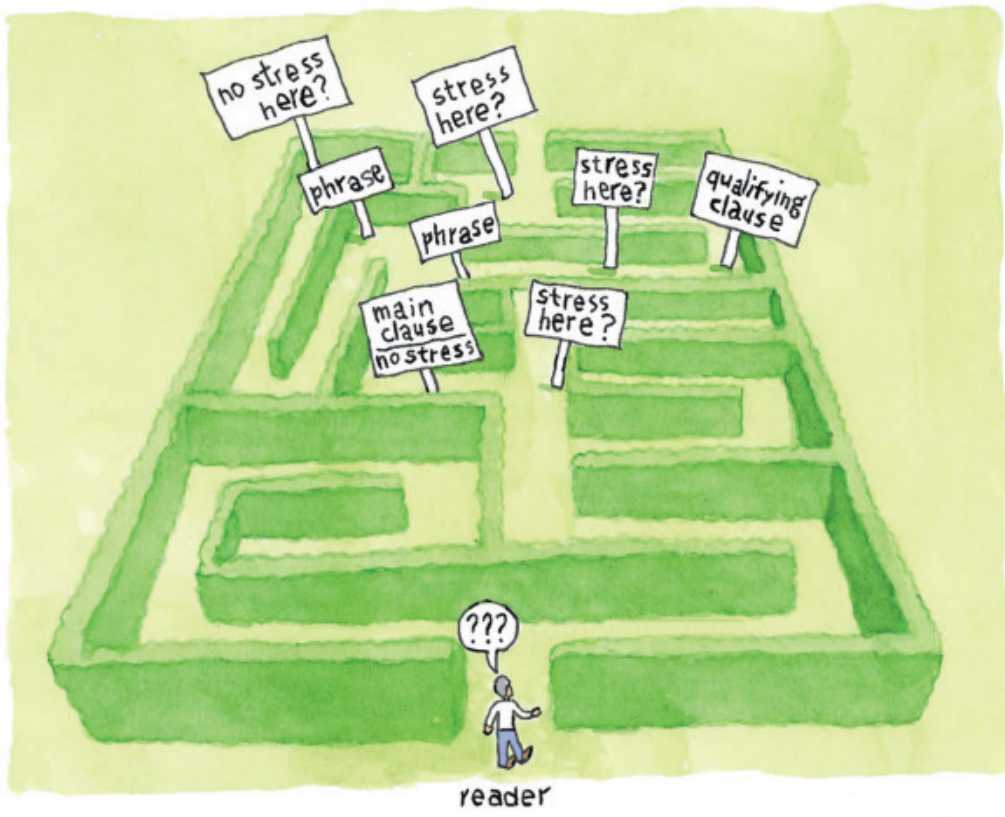
In looking at the writing of thousands of scientists, I have calculated that almost 46 percent of all scientific sentences force their readers to become coauthors. No wonder we, as readers, so often feel relieved to have made our way to the end of a scientific document. No wonder we so often at that moment suffer a real sense of fatigue. We have had to work far too hard—and with questionable results.

What to Stress

Looking at some typical scientific sentences of two clauses or more, I use a double slash (//) to indicate any moment in a sentence when we could insert a period without offending any rules of grammar. We will find a // at the end of every main clause without a stress position because, as a proper main clause, it could stand by itself as a sentence; but often we will find that double slash a few words later as well, where the sentence once again could have properly been brought to an end. A simple single clause in an English sentence averages from 12–15 words; scientific documents average 26–29 words per sentence. Thus, the average scientific sentence contains an average of two clauses, which invites the possibility of a main clause first problem. Here is one example sentence:

> Inhibition of CMA in heart unexpectedly confers resistance to stress-induced cardiac dysfunction in both pressure overload and myocardial infarction models, which is opposite to MA deficiency in heart, and differs from CMA deficiency in other tissues.

This sentence could have ended at the first comma, without offending any grammar teacher, because those 20 words form a main clause; the rest of the sentence is a qualifying clause—a "which" clause. The 20-word main clause can stand by itself as a sentence; the qualifying clause cannot.



Tom Dunne

Reading a sentence becomes a maze of comprehension problems when readers are given conflicting instructions on what parts of the sentence to stress. Readers encountering positions in the sentence where they expect a cue to stress something will experience a kind of interpretive tension when they do not receive that cue. They are forced to double back and see if they missed something while they also try to continue forward reading the sentence and interpreting its meaning.

But the trouble starts earlier than that comma. As a first-time reader, when I reach the 12th word, "dysfunction," I have already experienced a whole main clause—and therefore have been handed enough for a whole sentence. Words 13–20 are a phrase that further describes where the dysfunction might occur. The natural weight of that initial 12-word main clause suggests that something in the sentence so far deserves emphasis:

> Inhibition of CMA in heart unexpectedly confers resistance to stress-induced cardiac dysfunction //

But because, as a reader, I *could* stop there, my forward motion toward the expected closure of the stress position that did not materialize raises a kind of interpretive tension in me. I could stop; I perhaps want to stop; but I am not allowed to stop. It is both a retroactive-leaning and a forward-looking problem.

Retroactively, the question becomes, How should I have been reading these 12 words? There is enough for a full sentence here; should I already have stressed something? And if so, what? Consider the number of reasonable candidates for stress: "inhibition of CMA"; "in heart"; "unexpectedly"; "confers resistance"; and "stress induced cardiac dysfunction." That makes five. But perhaps I should be stressing more than one. Or, importantly, believing the lack of punctuation here, which tells me not to stress anything yet, perhaps I should stress nothing. All of these decisions have to be made by the reader retroactively at the clause's end; but at that confusing and unconfident moment, the mind is also barreling forward to finish reading the sentence. Hence, the problem: We have been given two conflicting instructions at the 12-word mark—"stress something here" and "do not stress anything here." Thereafter, we will be reading units other than a main clause that tell us "do not stress anything here"; but at their end, we find a period that instructs us "stress something here." This structure causes a serious reading problem—highly likely to occur several times on every page.

It was the responsibility of the writer first to make those decisions for the reader and then to communicate them clearly. The sentence's structure, signaled by its punctuation, should allow the reader to continue reading forward without either mental interruption or undue interpretive burden. As readers, we should be able to trust that the most important material will appear in a stress position. If, as a writer, you can manage to do that for your readers on a regular basis, they will quickly learn to trust you.

So far, even though we have looked at only 12 words of our 36-word sentence example, we have already overtaxed our supply of reader energy for this sentence. Too much has been left to the reader being able to make reasonable guesses.

Here is the same example with double slashes for every time the sentence might have come to an end:

> Inhibition of CMA in heart unexpectedly confers resistance to stress-induced cardiac dysfunction // in both pressure overload and myocardial infarction models, // which is opposite to MA deficiency in heart, // and differs from CMA deficiency in other tissues. //

A sentence is "too long" not when it exceeds a certain number of words, but rather when it has more viable candidates for stress positions than it has stress positions.

At each of those double-slash moments, the readers once again have to decide what, if anything, they should be stressing along the way. Recall that there were five reasonable candidates in the first 12 words alone. The sentence sounds professional and dignified, but it is an interpretive headache.

This sentence was written by a highly intelligent and professionally competent scientist; but if we try hard to decide for ourselves as readers which pieces of information we should stress here, we come away with a mistaken sense that she is somewhat disorganized or perhaps just a pedestrian thinker. Over multiple occurrences of this decision-making on every page of the document, the cumulative effect is

hard for the reader to bear: Once you have guessed wrong as to what the writer meant in one clause, all your subsequent guesses will be based more on sand than on concrete.

Here is the revision the writer and I devised, based on her decisions concerning stress-worthiness. We made sure not only that each main clause contained stress-worthy information, but that the stress-worthy material appeared at the main clause's end, in the stress position created by the period. That structure eliminated the "stress something" versus "stress nothing" conflict:

> Inhibition of CMA in heart unexpectedly confers resistance to stress-induced cardiac dysfunction. This happens in both pressure overload and myocardial infarction models: In heart, this is opposite to MA deficiency; in other tissues, it differs in CMA deficiency.

As readers, we can feel confident in leaning forward to the moments of stress signaled by the periods, the colon, and the semicolon. Having perceived, clearly and easily, what she wanted us to stress, we are leaning forward to the next sentence.

It is in our best interest, psychologically, to believe we are as competent a reader as the author is a writer. The truth of the matter is that our noncomprehension can be real—and is often the fault of the author.

Hidden Problems

Another example, at first glance, might seem relatively unproblematic. The worst of all sentences are not those that cry out how challenging they are; instead, they are those that seem faultless but fail to deliver their message to a majority of the reading audience.

> The problem continues to flourish, // despite efforts by Congress to enhance opioid prescription monitoring // to limit drug diversion // and trafficking, // suggesting that a novel strategy is needed. //

From the brain of the writer to the brain of the reader, how could this sentence go awry? Let me write for you an accurate yet annoying single-sentence tour guide for this sentence's readers, describing its reading as a slow-motion process. I intend it to burden you consciously in the way your mind subconsciously struggled while reading the sample sentence for the first time.

Right off the bat we are handed a full main clause ("The problem continues to flourish"), which could easily have been the end of the sentence, allowing us a stress position, but it refuses to end and is followed by a phrase ("despite efforts by Congress"), the efforts of which are then described by the phrase "to enhance opioid prescription monitoring," with that "monitoring" then getting identified by the phrase "to limit drug diversion," which could have ended the sentence

The worst of all sentences are not those that cry out how challenging they are. They are those that seem faultless but fail to deliver their message to a majority of the reading audience.

but instead adds the feature "and trafficking," which certainly could have been the end of the sentence, but, to our increasing sense of burden, is followed by a whole new qualifying clause ("suggesting that a novel strategy is needed"), which, though new it may be as a grammatical structure—and one that ends with a period, thus signaling the single stress position in the sentence and inviting emphasis, even though it is only a qualifying clause—sounds suspiciously like the main clause we encountered so long ago, maybe.

I trust my sentence was burdensome to read—one long, rambling sentence, with several interruptions and backward looks, always frustrating your journey toward closure. Its only stress position contained the anti-stress word "maybe." Whereas you, reading the original for the first time, may not be conscious of having to make all these judgments and revisions of judgments, your reading process is being taxed in much the same way as it was by my guided tour. If you have 10 readers try to rewrite this example, producing a stress position for everything they think the writer intended us to stress, you will be likely to get anywhere from four to eight different revisions.

When the author thought about revision in this manner, here are the decisions he reached: Two stress positions were needed, one for the problem's "flourishing" and another for the need to devise a new strategy to solve it; and the attempts by Congress ought not to be stressed, as they are there mainly to help produce context for the rest of the sentence.

Given the newfound clarity of the author's intentions, the revision was relatively easy to accomplish. Congress's activity deserved only a phrase, near the beginning of the sentence, where contextualizing naturally takes pace. Care should be taken to warn the reader that "limiting" will be applied to a pair of activities—to drug diversion and to trafficking. All that, in the "don't stress me" unit of a phrase, should lean forward to a main clause, ending with "flourishing" in a stress position. Then there should be another main clause, with another stress position, to signal the importance of the need for a novel strategy. This revision accomplished, the reading becomes easy, forward-flowing, and confidence-breeding:

> Despite efforts by Congress to limit both drug diversion and trafficking by enhancing opioid prescription monitoring, the problem continues to flourish: A novel strategy is needed.

If we could provide this kind of clarity for each of the 100–150 sentences found in a typical journal article, think what a joy scientific reading might become.

Revision Process

Are you beginning your sentences on a regular basis with a main clause that has no colon, semicolon, or period at its end? As a new part of your revision process, decide whether that main clause contains stress-worthy information or not. If it does, you have two remedies: Leave the main clause at the beginning, ending with a colon or semicolon, whichever suits the occasion; or move this main clause to the end of the sentence, where it can benefit from the stress position created by the period. If, on the other hand,

you decide there is no stress-worthy information in this main clause, you would do well to demote the main clause structurally by making it either a qualifying clause or a phrase. When you get used to doing this on a regular basis, your documents will become more and more reader-friendly.

It is better not to begin trying these new methods in the process of writing a first draft. They will constantly interrupt your normal procedures, because they will be challenging many of your long-held writing habits. Use them at first as part of a revision process. Take what you have written and discover for each sentence the answers to two important questions: Does everything I want the reader to stress occupy a stress position? And do any of my main clauses end without the presence of a colon, semicolon, or period? You will soon grow to recognize when there is a stress position or main clause first problem.

It may well be a bit of a struggle at first to make the appropriate structural revisions. Overcoming long-established habits is difficult indeed. But the more you change them, the better you will get at it. If you fail in your effort to revise a given sentence, let it go. Succeeding 50 percent of the time on a first attempt is a good result.

If you persevere, after just a few documents, you will find these new principles becoming habits that will eventually infiltrate the initial drafting process. After a while, it will all become natural. This process will slow you down for a few documents, but once it becomes part of your initial writing process, your writing will take you less and less time, with better and better results.

Here is an example of a revision process where a main clause does not contain stress-worthy information and needs to be demoted:

> TB is one of the top 10 causes of death globally, // and now the leading cause of death from a single pathogen worldwide, // surpassing HIV.

This sentence begins with an 11-word main clause without a stress position; we then get a phrase that could have ended the sentence; but we are asked to extend our energy for another two-word phrase, "surpassing HIV." Was "surpassing HIV" intended to be the only emphasis? If so, why are those two words presented to the reader in a lowly phrase?



Writers who review every sentence they have written to ensure that everything they want the reader to stress occupies a stress position, and that their main clauses end with a colon, semicolon, or period, create a clear path for readers to comprehend their meaning without confusion or fatigue.

What if the author wanted us to stress "top 10 causes of death"? In that case, we need to move the main clause it inhabits to the end of the sentence; and we to need get that top 10 statistic (instead of "globally") all the way to the stress position at its end. In that scenario, the work of the word "globally" has already been done by the word "worldwide." Here is the result of that revision:

> Now the leading cause of death from a single pathogen worldwide, surpassing HIV, TB has become one of the top 10 causes of death.

But what if I guessed wrong about the writer's intentions? What if the most noteworthy piece of information here was intended to be the seemingly redundant term "globally"? By reducing most of the rest of the sentence's information to a mere contextualizing phrase, which would then clearly lean forward to the sentence's main clause, we could ensure that "globally" will shine in the stress position's moment of closure. Then the repetitive quality of "globally" would be interpreted not as wordiness but as emphasis:

> Now the leading cause of death from a single pathogen worldwide, surpassing HIV, TB has become one of the top 10 causes of death globally.

But what if the author instead wanted us to stress "single pathogen"? Then that term should inhabit the sentence-ending main clause:

> One of the top 10 causes of death globally, and now surpassing HIV, TB has become the leading cause of death from a single pathogen.

What if the author also wanted us to stress that TB has now surpassed HIV? Then we create for HIV another main clause—with its own stress position:

> One of the top 10 causes of death globally, TB is now the leading cause of death from a single pathogen: It has even surpassed HIV.

Where grant applications are concerned, carefully crafting your sentences so that every piece of stress-worthy material inhabits its own stress position can lead directly to funding. There are lots of good ideas out there, asking to be funded; but if your good idea is written so clearly that your fund-controlling reader is both properly instructed by it and delighted by it, you are likely to triumph over the competition.

Types of Stress

A major cause of these ubiquitous problems in scientific writing is, I believe, that we never alter our sense of what the writing task is supposed to accomplish once we have completed our schooling. There, our purpose was to prove to our teacher that we had done enough work to deserve a good grade. Our rhetorical task was one of *demonstration*. In the scientific world, the task changes. Now we, not some teacher, are the experts in what we know. We write to convey that knowledge to readers who do not already possess it. Our rhetorical task has become one of *communication*.

The scientific writer—in every single sentence—must send readers

the correct instructions for how they should put all these words together. Without knowing the crucial importance of the stress position, and without understanding how different units of discourse (main clause, qualifying clause, and phrase) send different instructions concerning what information should and should not be considered important, we cannot control our readers' interpretive process.

When we are 15 years old, we have been writing for about 10 years. We have developed in our brain a sentence-writing "machine." It has a "start button" on it. If you are called on to write a sentence, you push the start button, and the machine bursts into action: "Choose a subject. Choose a verb. Unravel your complement. Put a period." You want to write another sentence? Push the button again. Then you turn 18, go to college, and start reading primary sources instead of textbooks. It does not take long for you to discover that these important people sound different from you. Two main reasons: They use a lot of hard words; and their sentences go on for twice as long as yours. So when you have to write a college paper, what are you going to do? You are going to do what you always have done: You will push the button. "Choose a subject. Choose a verb. Unravel your complement. Put a period . . . No! I have to go on twice as long as I used to. I'll put a comma and keep going." And on you go. You are constantly producing a main clause first problem. You used to write primarily one-clause sentences. Now you have to write two-clause sentences. No one has taught you the difference.

For all those precollege years, because most of your sentences were made up of just a single main clause, your act of beginning the writing of a sentence was exactly the same as your act of beginning the writing of a main clause. That process became a habit. There was no one around later on to tell you that if you usually begin your sentence with a main clause but give your reader no stress position, your reader is already in deep trouble. You have already lost control of the structure of your own sentence. You have lost the ability to indicate what the reader should stress.

To remedy this deficit, I have devised a four-part typology of two-clause sentences. It should cover almost all of the two-clause sentences you will ever have to write.

In the first type, I have written a sentence in which two main clauses are separated by a comma. The period at the end establishes a single stress position. In thinking more about the sentence, I decide that the first main clause contains something worthy of stress; but the more I contemplate these two statements, the more I believe that the second one deserves its own separate unit. How can I produce both a stress position for the first clause and isolation for the second? To do so, I put a period at the end of the first clause; and then I begin the second with a capital letter. Both now have stress positions. They live separate lives.

Take what you have written and ask yourself for each sentence, Does everything I want the reader to stress occupy a stress position?

In the second type, again, my sentence has two main clauses, separated by a comma. Again, the first main clause contains something important enough to be stressed. But the relationship between the two clauses is different here: The second clause restates or exemplifies the first. How can I both create a stress position for the first and advertise that the reader should be expecting a full main clause restatement of it in the second? To do so, I put a colon at the end of the first clause; and I begin the second with a capital letter, indicating it will have enough in it to stand by itself as a whole sentence.

In the third type, my sentence again contains two main clauses, separated by a comma; and again, the first clause requires a stress position. But the relationship between the two clauses here is different: The first clause is part one of a two-part thought; the second clause is the completion of that thought. Both require stress positions. To signal this structure, I put a semicolon at the end of the first clause. Semicolons tell the reader, "Hold onto part one, stressing its end; and now part two is beginning, with stress expected at its end."

In the fourth type, this time they are not both main clauses: One is a qualifying clause. How can I produce for the main clause a stress position? I can move the main clause to the end of the sentence: There it will benefit from the period creating a stress position. If the qualifying clause, appropriately, contains no stress-worthy material, how can I signal the reader both that it is over and that no stress should be applied? I can move the qualifying clause to the beginning of the sentence: There, by using a comma, I can signal the reader not to stress anything in it.

If we review these four revised sentence types together, we discover something powerful and elegant: Their purposes are distinguished from one another by the punctuation marks that occur between the two clauses. Taken together, they comprise the four main punctuation marks of the English language—period, colon, semicolon, and comma. If you can master the differences these four make in the middle of multiclause sentences—the different instructions they send to the reader—then you can control any two-clause scientific sentence, no matter how long or complex. These marks of punctuation send to your readers two important instructions: They tell the reader whether or not to stress something in the first clause; then they reveal what the relationship will be between the first clause and the second.

If all scientific writers, writing in English, could produce a stress position for every morsel of material that requires stress, all readers of that prose could leave off their jobs as coauthors and become pure readers—always moving forward both within a sentence and from sentence to sentence. Ideas and information could be communicated accurately from writer to reader. And blissfully, readers would arrive at the end of every document delighted to have encountered it, with no trace of unnecessary fatigue.

George D. Gopen is professor emeritus of the practice of rhetoric at Duke University, where he taught in both the English department and the School of Law. He created the Reader Expectation Approach to writing, which emphasizes how scientific and other professional writing works for readers. Website: georgegopen.com

Is Garlic Mustard an Invader or an Opportunist?

Originally thought of as simply harmful to native plants, this invasive herb has been spreading for far more complex reasons.

Michael Anderson

The first time I saw garlic mustard I did not know enough to be alarmed. I first noticed the plant early in the spring of 2005, while wandering the grounds of my new home at Macalester College's Ordway Field Station in Minnesota, where I had just been hired as the resident caretaker. The plant was one of the few green things in the forest at that time of year, but I could not find it in any of the station's field guides. The following summer, I learned from local botanist Karen Schick of the Friends of the Mississippi River that the plant was garlic mustard (*Alliaria petiolata*). Visibly concerned, Schick informed me that the plant was invasive in Minnesota. Garlic mustard lives for two years, with two distinct growth stages. The greenery I had first noticed were patches of yearlings called *rosettes*, a low-lying form that sprouts from fresh seed and remains green all winter. By June the following year, these had grown into thick stands of chest-high adults that looked like an invasion to me, now that I knew what I was looking at. Few native plants were evident between the tall stems, as if they were falling beneath an advancing foreign army.

A few years after my initial encounter with garlic mustard, I began to work with two Macalester professors—Mark Davis, the well-known invasion ecologist who spearheaded our research program, and Jerald Dosch, as well as dozens of gifted undergraduates—to learn about the connection between garlic mustard and native plant communities. Since then, garlic mustard has become one of the most intensively studied invasive plant species in the United States. The picture that is emerging from all this work provides an unusually detailed case study in the intellectual hazards of ecological research. Every aspect of the "invasion" of this species has turned out to be richer and more complex than it first seemed—regarding both its causes and its consequences, and even the term *invasive* itself.

The invasion of garlic mustard into my backyard forest is the tiny tip of a large iceberg. Globally, approximately 14,000 plant species have become *naturalized*, meaning plants that humans introduce to a new region that then form self-sustaining populations. Of these species, a smaller and more difficult to define fraction—perhaps 2,500 species—have become *invasive*, meaning they have grown numerous enough or they have large enough per-capita effects for them to be considered pests.

The term *invasive* is controversial, due to wide variation in its intended meaning, not to mention its xenophobic and militaristic connotations. I use the term here because it is the most familiar and widely used descriptor of such species. To be clear, I use the term in the restricted sense established in President Barack Obama's 2016 executive order on invasive species: "a nonnative organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health."

Determining whether any given nonnative plant species is likely to be harmful enough to qualify as invasive is far from straightforward. The ecological and economic effects of such plants are notoriously difficult to assess and are controversial even among the scientists who study them. Estimates of the economic costs run into the billions of U.S. dollars. Invasive plant species are also often associated with diminished diversity of native plant communities and changes in the function of their ecosystems. However, determining the cause-and-effect relationships of such associations is one of the trickier aspects of studying species invasions. Garlic mustard, considered invasive not only in Minnesota but also in the entire northeastern quadrant of the contiguous United States, is an excellent example of the difficulties involved.

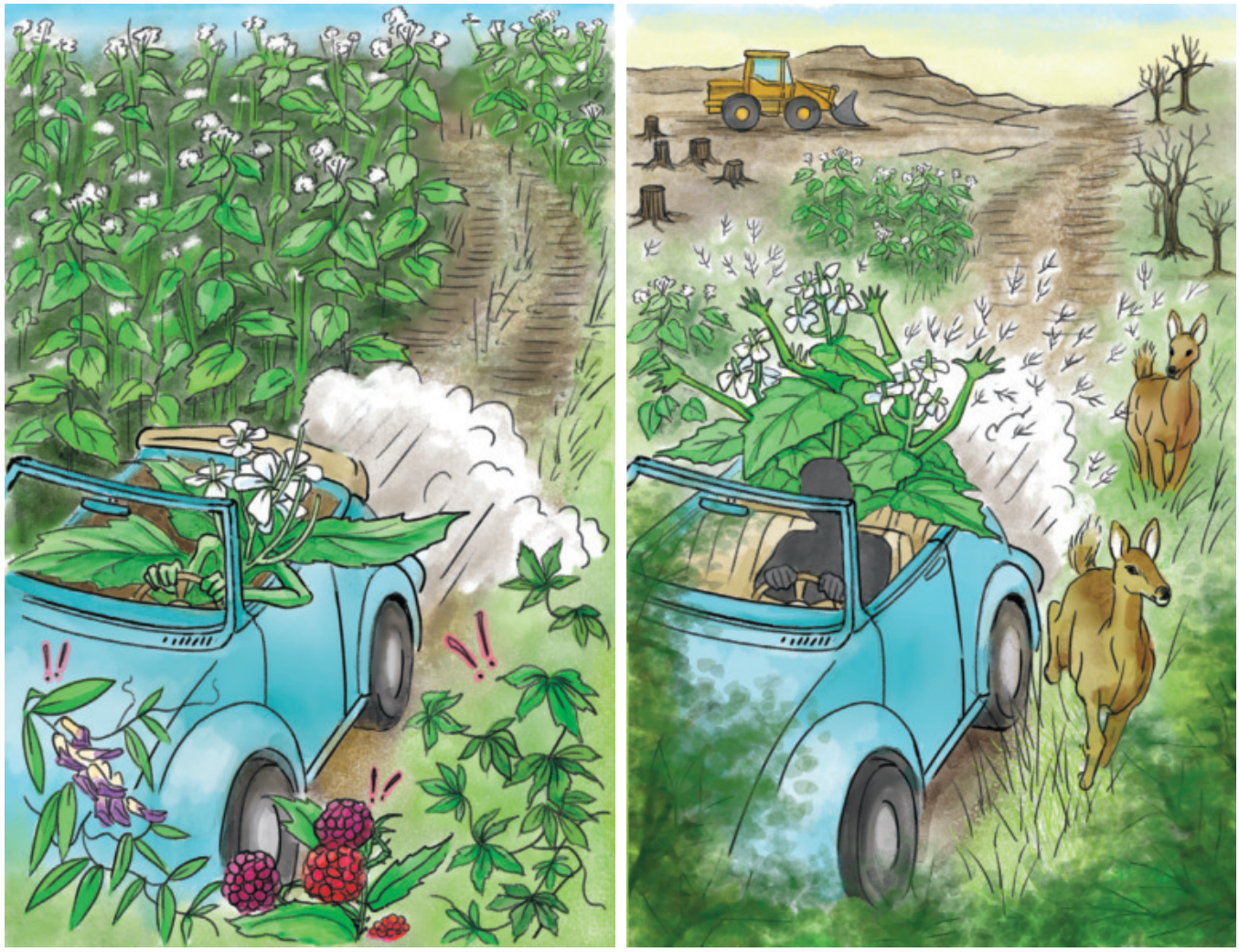
Early field surveys noted garlic mustard's tendency to form dense stands that contained low numbers and diminished diversity of native plants. Experimental studies conducted during the same period discovered that garlic mustard produced a variety of toxic compounds that wound up in soils inhabited by the plant. In laboratory experiments, these compounds inhibited the growth of fungi, including the kinds that form beneficial mycorrhizal symbioses with the roots of most plant species. Garlic mustard, as a member of the mustard family, is one

QUICK TAKE

The introduced weed garlic mustard has been expanding its range in North America for decades and is one of the most intensively studied plants in invasion biology.

Early studies noted diminished numbers and diversity of native plants in garlic mustard's presence, and postulated that they were outcompeted by the spicy weed.

A new view is emerging that garlic mustard is not causing these changes in plant communities, but rather its increase is a symptom of larger changes driven by humans.



Stephanie Freese

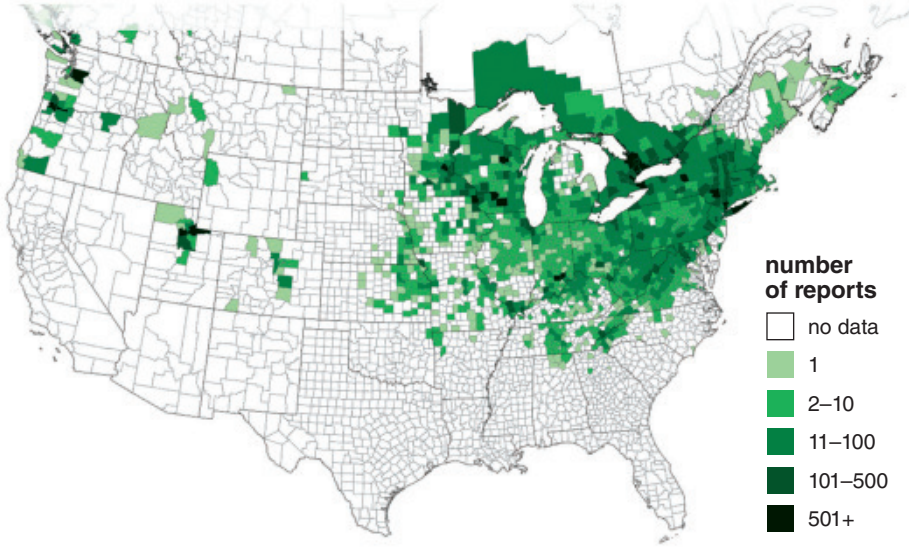
A well-known analogy in invasion biology involves asking whether an invasive species is truly the "driver" of change or merely a "passenger," an idea put forward in 2005 by Andrew MacDougall of the University of Regina and Roy Turkington of the University of British Columbia. In the case of garlic mustard, much work has focused on determining if this weed outcompetes native plants in North America, or if it is merely favored under the sweeping changes humans have made to ecosystems over the past several decades.

of the minority of species that does not participate in these symbioses. Therefore, it seemed likely that the "chemical warfare" waged by these compounds—an interaction known as *allelopathy*—probably allowed it to muscle its way into intact native communities. If that was the case, it also seemed likely that the plant was poised to cause significant damage to native ecosystems.

Invasive plants are often assumed to spread by outcompeting native species. In garlic mustard's case, this hypothesis is certainly plausible. The adult plants are tall, compared to other forest-dwelling herbs, which provides a significant light-gathering advantage in dim understory environments. The rapid growth of adults in their second year of life also seems likely to deplete soil resources such as water and nutrients, lowering their availability to smaller native plants. And garlic mustard's possession of allelopathic compounds gives it a novel weapon in its struggle for existence with native plants. If garlic mustard owes its success to such advantages, then—to borrow an analogy developed by Andrew MacDougall of the University of Regina and Roy Turkington of the University of British Columbia—it could be "driving" the ecosystem changes that seem to be associated with it. In other words, garlic mustard could *cause* diminished abundance or diversity of native plants by directly harming them.

This possibility has caused a great deal of concern among researchers, land managers, nature enthusiasts, and landowners in states across the plant's naturalized range. Descriptions of garlic mustard in informational materials provided by land management organizations often include such terms as "aggressive," "highly invasive," and "destructive," and commonly reference its superior competitive ability and allelopathy. Such organizations often arrange volunteer events billed as "garlic mustard pulls" that aim to "clean up" "infested" areas by hand-pulling garlic mustard plants by the thousands. In 2013, the state of Minnesota added garlic mustard to its list of prohibited noxious weeds, citing competitive ability and allelopathy in its description of the effects associated with the plant.

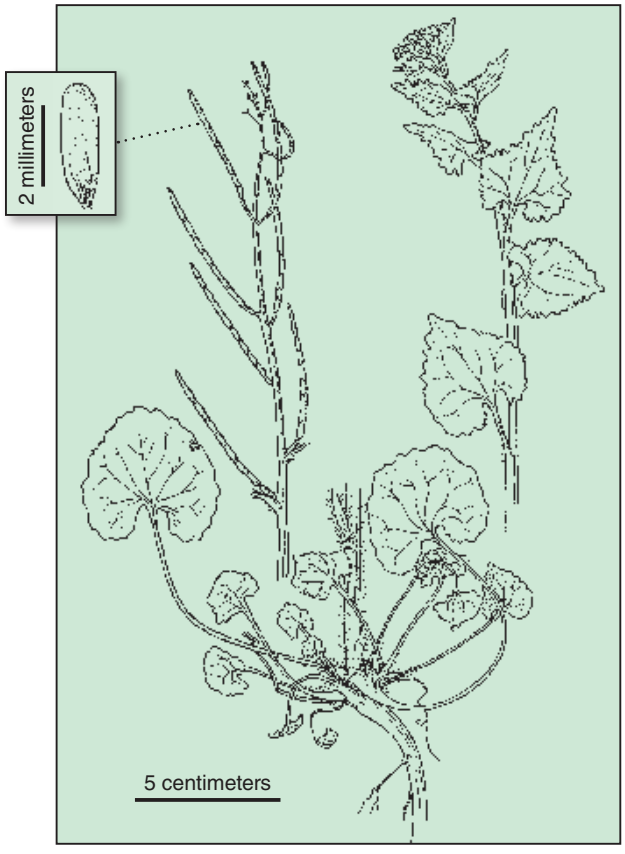
However, things are not always as they seem, especially in ecology. As garlic mustard research has expanded and diversified over the past decade and a half, the simple cause-and-effect scenario that initially seemed so clear—and so alarming—has begun to yield to a picture that is more complex. Further work suggests that garlic



USDA/eddmaps.org

Garlic mustard was first recorded in the United States in 1868 on Long Island, New York; since then, its range has expanded across the Northeast, as well as other parts of the country. The plant's spread became a focus of concern beginning in the late 1980s. In the interim, many environmental changes occurred that may help explain garlic mustard's astonishing increase in number.

mustard is not quite the superior competitor it appeared to be, and that its spread may have as much to do with large-scale environmental changes as with characteristics of the plant itself.



Garlic mustard has a fixed two-year lifespan. During the first year, it grows low to the ground in a vegetative rosette that stays green over the winter. In its second year, the plant bolts, produces numerous seeds, and then dies. This life strategy allows first-year rosettes to get a head start on the season, unlike the native plants that die back to their roots. It also allows garlic mustard to prolifically disperse into new habitats and expand its population wherever its seeds germinate.

Is Garlic Mustard a Super-Competitor?

If garlic mustard is an aggressive spreader able to outcompete its way into intact ecosystems using chemical weapons, one puzzling question is why it has taken so long to spread. Garlic mustard seems to have been introduced by settlers to the United States in the mid-19th century, probably for culinary use: The earliest known record of its occurrence is from Long Island, New York, in 1868. By 1918, herbarium records indicate that it had arrived in Illinois. However, it was not until the late 1980s that its rate of spread had increased enough for it to be seen as a potential problem in the United States. Why the delay?

Another inconsistency in the garlic-mustard-as-superior-competitor scenario is the fact that continuing field surveys have failed to observe the clear negative impacts on native communities that were initially expected. At Ordway, looking for such impacts has been one of our main objectives. We have observed the understory plant community in our oak forest in a set of 180 research plots every year since 2014. When we began the experiment, we expected that if garlic mustard were a strong enough competitor to be driving ecosystem changes, we should see stronger or more consistent negative correlations between garlic mustard and native species than we saw between native species. For all species, we measured both the size and number of plants in our research plots using the percentage of each plot's area covered by a given species. For native species, we also measured diversity, the number of native species present in each plot.

One difficulty with studying plants in the forest understory is that there are patches of ground full of plants and others where plants are sparse. Because of the low light available in most locations across the forest floor, plant density tends to be low in a large fraction of research plots that are placed at random or regular intervals—so low, in fact, that plants in such plots are unlikely to be competing at all. Plant densities high enough to potentially trigger competition tend to occur in areas with high light availability, such as a gap in the forest canopy caused by a recent tree fall. To account for this difference and maximize our chance of finding any evidence of competition that might exist, we analyzed plots with high or low plant density separately.

In the high-density plots, garlic mustard was negatively correlated with abundance and diversity of native plants, especially woody species. However, the strength of the correlations and their consistency across years were similar to those of the most common native species at our site. Thus, if the negative correlations are due to competition (an additional wrinkle not discernible from our field data), garlic mustard's strength as a competitor is about what we would expect from a native plant that is as common as garlic mustard. Our results agree with continuing field studies that have found negative associations between garlic mustard and native plants only uncommonly. Even when they have been found, those associations tend to be weak or inconsistent over time.

Douglas, G. W., et al (Editors). 1998. Illustrated Flora of British Columbia, Volume 2 © Province of British Columbia

Garlic mustard's lack of competitive dominance in the field makes sense in light of further laboratory studies of its antagonistic abilities. Head-to-head competition experiments, which compare the growth of garlic mustard and other plant species when grown alone versus together in the same pot, have found that garlic mustard is not the overwhelmingly dominant competitor it was initially feared to be. Some native species do seem to get beaten out in such trials, based on how strongly they are inhibited by garlic mustard and how strongly they inhibit the invader in return. However, many native species seem to be a relatively even match, and a few even outcompete garlic mustard.

More detailed studies of garlic mustard's allelopathy have also revealed that production of the toxic compounds varies widely among garlic mustard populations, environmental conditions, and even season, and that native plant species differ widely in their susceptibility to allelopathy. Garlic mustard also has self-inhibitory effects. Competition from adult plants strongly inhibits the smaller rosettes, particularly in dense populations. The effect is strong enough that it may even be driving the evolution of weaker competitive abilities in the species, in order to diminish the inhibitory effect of adults on their own offspring.

Native plant communities may also evolve in response to garlic mustard's presence. Both native plants and their mycorrhizal fungi appear to develop resistance to garlic mustard antagonism that increases with their time of exposure to the invader. This development of resistance even seems to be driving a coevolutionary response in garlic mustard. Tissue concentration of allelopathic compounds diminishes from younger to older populations of the invader in North America, likely due to the cost of producing them and the diminished benefits they yield in more resistant native communities. The growth rate of garlic mustard populations also appears to diminish the longer the species is in a given location, perhaps due to such decreased competitiveness or to the evolutionary "discovery" of invasive populations by North American soilborne pathogens and parasites. The upshot of all this further work seems to be that garlic mustard is less of a competitor than it seemed at first, and that its competitive ability is likely decreasing over time.



Jim West/Alamy Stock Photo

Volunteers clear garlic mustard from a public park as part of an event to pull up the plants. Such events became popular among conservation and stewardship organizations, because garlic mustard was thought to be pushing out native plants. New research is questioning this management strategy, however.

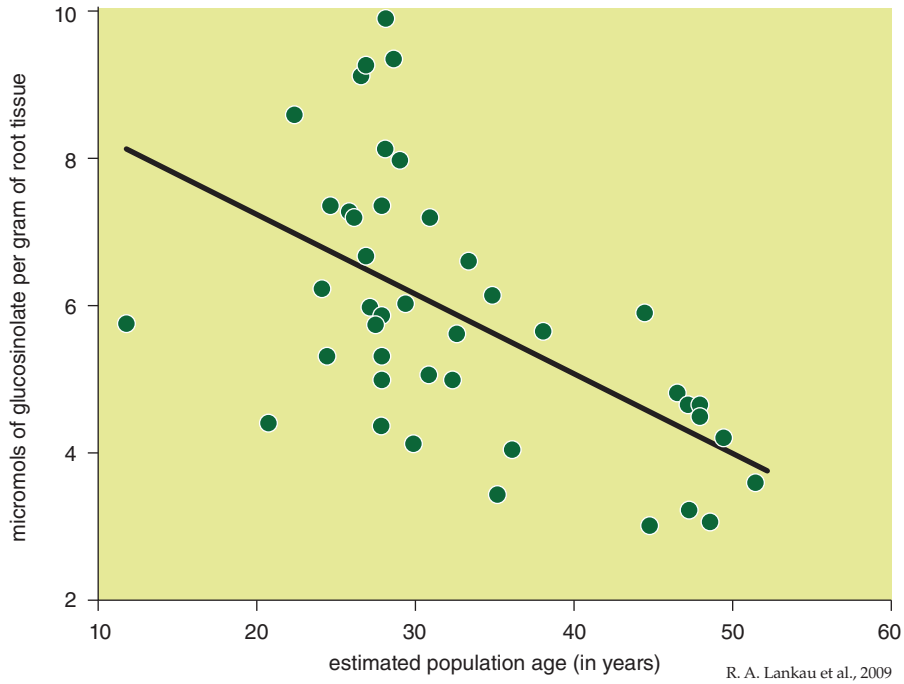
Alternative Explanations

If garlic mustard invasion is not due to the plant's superior competitive ability, quite a lot of alternative explanations are plausible. Invasion biologists have developed so many hypotheses to explain species invasions that another focus within the discipline has been classifying these hypotheses into broader conceptual frameworks. Continuing work with garlic mustard has shown that a large fraction of these alternative hypotheses are also likely to help explain the plant's spread. Many of these alternatives would put garlic mustard in the role of "passenger" rather than "driver" of ecological change. In other words, the spread of garlic mustard might be an effect rather than a cause of changes that are occurring in native ecosystems. The plant may largely be riding on the coattails of favorable environmental changes driven by humans.

The North American environment to which garlic mustard was introduced in 1868 is not the same environment across which its population has been recently expanding. In the past century and a half, human populations in garlic mustard's invaded range have exploded in number, carved our way deeply into the pre-European landscape, and changed our technology and lifestyles in ways that have increased the environmental footprint left by each one of us. These human-made changes have ripple effects in the ecosystems associated with us—affecting even native species—favoring some organisms and disfavoring others.

Both native plants and their mycorrhizal fungi appear to develop resistance to garlic mustard antagonism.

At the same time, growing human-generated carbon dioxide emissions have not only increased the atmospheric concentration of this important plant resource, but also the average global temperature by more than 1 degree Celsius. Temperature increases have been even greater in garlic mustard's invaded range—more than 1.7 degrees Celsius in Minnesota, for example—



Garlic mustard's pungency derives from a class of compounds called *glucosinolates*, which serve as a defense against many herbivores and can also chemically suppress soil fungi that are symbiotic with most plant species. In North America, older garlic mustard populations have lower tissue concentrations of these compounds, perhaps indicating that the plants garner diminishing returns on producing them, perhaps due to evolved resistance in native species.

and have brought with them altered patterns of seasonal temperature, precipitation, and an extended growing season. Any of these factors could be involved in garlic mustard's invasion.

The success of any species in a particular place is a complex function of its history there, its inherent traits, and the qualities of the environment around it. Invasive species often seem to possess traits that the native species lack and that allow them to interact differently with the environment. Looking for such differences has been another major focus of research on garlic mustard, including ours at Ordway. The picture emerging from our work and other research in our field suggests that garlic mustard differs in many ways from common native plants. However, these differences may be especially favorable for invasive spread following recent, human-caused environmental changes. There are many such changes, and the spread of garlic mustard may require more than one.

Seasonal Timing

One way garlic mustard differs from the native herbs in North American forest understories is in its seasonal timing. Garlic mustard utilizes a strategy called *extended leaf phenology*, which means that it is green and active during portions of the year when most native species are dormant. Nearly all the native herb species in Ordway's forest have a deciduous seasonal strategy. They lose their leaves and stems in the autumn, spend winter protected in the soil as some form of dormant rootstock, and then reemerge the following spring after the worst of winter has passed.

Garlic mustard's extended phenology derives from its two-year life cycle. The first-year rosette stores much of its photosynthetic product below ground rather than using it to grow. Its above-ground tissues remain green through winter. The following spring, the rosette taps its stored resources to grow into a tall, leafy adult that emerges before the leaves of the canopy trees. At Ordway, adults flower by mid- to late May—earlier than most native species—and pollinated adults fill seed pods and begin to die back by mid-July, before growth has peaked or flowering has begun for most of the native species.

Leafing out earlier in the year than the canopy trees and retaining active leaves later in the year gives garlic mustard access to more total light over the course of the year than the deciduous native herbs receive. Its activity during the spring and fall "shoulders" of the growing season also provides access to more intense light than is available closer to the middle of the season, when the dense canopy of the trees plunges the understory into deep shade. Earlier spring emergence gives garlic mustard access to more of the pulse of water and nutrients made available by melting snow and thawing soils, and decreases its exposure to competition for these resources. The potential advantages provided by extended leaf phenology appear to be great enough that a high proportion of other invasive plant species in North America seem to possess some form of it.

Although the hypothesis that extended leaf phenology aids invasion in North American forests makes sense, it also has a few issues. One is the obvious follow-up question: If extended leaf phenology is advantageous for invaders of North American forests, why has it not evolved in native plants? A likely answer is that the advantages provided by extended leaf phenology are contingent on recent changes in the North American climate. Many invasive plants with extended leaf phenology evolved the trait in their home ranges of Europe and Asia, where the climate during the shoulders of the growing season has historically been more predictable from year to year than in North American deciduous forests. Their success in their new home may indicate that the North American climate is becoming more similar to that of their Eurasian homelands. A second issue is that many plants with extended leaf phenology that have been imported to North America from the same home range have failed to become invasive. So even if the match between extended leaf phenology and climate change contributes to invasion, it cannot be the only factor. As it turns out, several other unusual traits of garlic mustard may aid in its recent spread in North America, as they interact with additional human-induced changes.

Defense against Herbivory

Garlic mustard also seems to differ from native herbs in its interaction with herbivores. For those who have not had the pleasure, the name *garlic mustard* is a surprisingly accurate description of the plant's odor and flavor. I can personally attest that its leaves make a nice base for pesto and a tasty addition to

salad. Its odor and flavor derive from a class of sulfur-containing compounds that permeate the tissues of most species of the mustard family. Ironically, the likely purpose of these compounds is to produce the opposite effect they have on humans: to make animals less likely to eat the plant. These compounds appear to work quite well. Garlic mustard has few natural enemies, particularly in its invaded range.

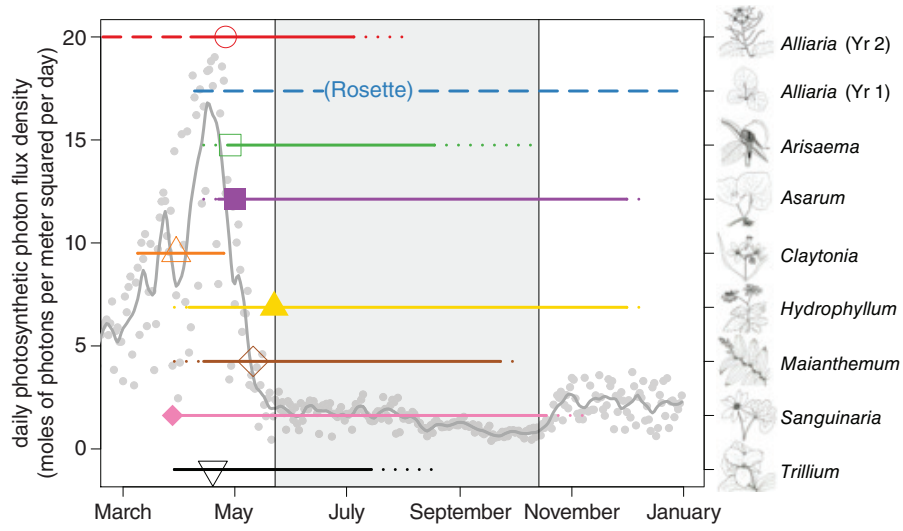
One of the most common large herbivores in American deciduous forests, white-tailed deer (*Odocoileus virginianus*), avoids the plant. Deer's aversion to garlic mustard has been widely noted across its invaded range. At Ordway, this behavior is also apparent: In four years of detailed surveys, we have only observed deer herbivory on four individual plants, despite the fact that garlic mustard is the second most common species in the understory. The deer do eat native species, in high quantities and in rough proportion to their occurrence. This selective feeding may clear the way for garlic mustard to spread.

Even if this selective feeding helps drive garlic mustard invasion, however, the scale of the plant's resulting spread may once again ultimately result from recent human-induced changes. In contrast to many species that have declined with human developments, white-tailed deer populations have expanded alongside them. Humans have removed or greatly diminished many of deer's natural predators such as wolves and coyotes. The habitats we love to create for ourselves—especially agricultural and suburban landscapes, with lots of food crops and oversized flowers and fruits—are also the favorites of white-tailed deer. Deer are now considered overabundant in many parts of their range, including Ordway, where the Minnesota Department of Natural Resources has estimated that there are more deer than available resources can support in the long term. Due to their large size, rapid reproduction, and voracious consumption, deer overabundance has a wide range of direct and indirect ecological effects. As their populations have expanded with human-altered habitats in recent years, it seems likely that their selective avoidance of garlic mustard can help explain the expansion of the plant.

One of the most striking ways to test this hypothesis is by using *exclosures*: fences that keep deer out of specific areas. Exclosure studies of garlic mustard have become common over the past decade and a half across the plant's naturalized range. In 2018, we initiated one in the oak forest at Ordway.

Our results so far align with most (but not all) such studies: Removing deer harms garlic mustard, too. At Ordway, fewer garlic mustard plants grow within exclosure plots than outside them, and fewer adult plants are represented among the tallest plants in the plots. After two years of exclosure, garlic mustard adults represented nearly 50 percent of the tallest plants in our plots outside the fences, but less than 10 percent inside.

However, removal of deer may not be enough to shift the balance back toward native species. One recent study found that exclosure alone did not affect garlic mustard abundance, and only had modest effects on native plants. Maximum native species abundance was only achieved with the additional step of sowing their seeds. This result indicates that the ability of some native species to disperse into available space is limited, and highlights another of garlic mustard's trait differences that could contribute to invasiveness: its dispersal strategy.



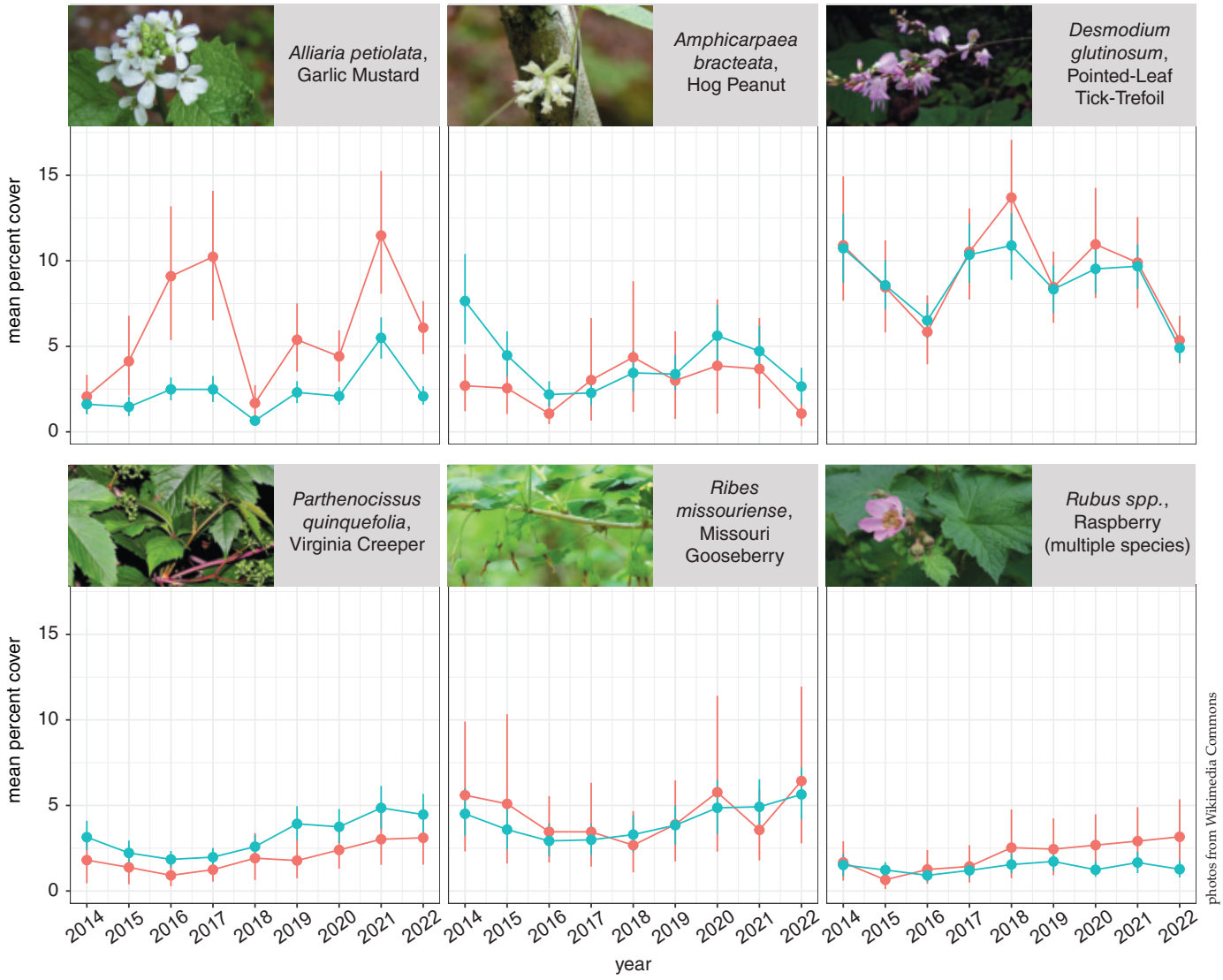
J. M. Heberling et al., 2019.

Garlic mustard rosettes (*blue and red dashed lines*) and adults (*red solid line*) have extended growing seasons compared with seven herb species native to North American deciduous forests. Horizontal lines indicate the median growing season length, from leaf emergence to dormancy, for each species. Garlic mustard is one of the earliest plants to emerge in the spring and also one of the first to produce seeds. The overwintering rosettes continue to photosynthesize into the autumn and winter, long after other plants have died back for the winter. The gray shading marks the period of leaf cover by canopy trees.

One of the most common large herbivores in American deciduous forests, white-tailed deer, avoids garlic mustard.

Dispersal and Disturbance

A basic problem all plants need to solve is how to spread themselves or their offspring into new habitable areas, given that they are unable to move. A staggering array of plant dispersal strategies have evolved to solve this problem. A single best strategy does not appear to exist; rather, the costs and benefits of various strategies differ across environmental conditions. The dispersal strategy used by garlic mustard in forests like the one at Ordway appears to be different from that of the native plants and, again,



Garlic mustard (*top left*) has grown in average percent cover since 2014 in a large canopy gap in the oak forest at Ordway Field Station in Minnesota, compared with five other common native plant species. Sampling plots within the large canopy gap are represented in red; plots within the understory are represented in blue. (Figures courtesy of the author.)

may give it an edge in capitalizing on recent human-induced changes.

Garlic mustard produces a lot of seeds—several times the number produced by its native neighbors of similar size at Ordway. If you jostle a garlic mustard plant that has gone to seed, the seedpods burst open, flinging their contents up to two meters away. You can hear the seeds pour down like tiny rainstorms to the ground below. Garlic mustard's high seed output is a result of its fixed lifespan, in which the plant reproduces only once in its lifetime, right at the end. Reproduction by species with fixed life spans is often called *big bang reproduction*, since these species will produce as many offspring as possible in their single reproductive effort.

The benefits of high seed production to garlic mustard's invasive ability have been demonstrated in a variety of studies. At Ordway, we have observed garlic mustard spread into new tree fall gaps much more quickly than native species. It is intuitive that the rapid spread of garlic mustard would be a result of its high seed output. However, this result is far from a foregone conclusion. Making large amounts of seeds is often not the best way for a plant to spread. Seeds take time to germinate and often need specific conditions under which to do so. Garlic mustard seeds, for example, require the drastic temperature changes of a winter–spring cycle to break dormancy, and germinate much better on bare soil than on leaf litter. New sprouts also need time to grow large enough to support themselves, during which time they are vulnerable to all manner of ill ends.

To compensate for such seed-related shortcomings, many plants use a different strategy to spread: vegetative reproduction. The basic idea here is to spread by growing wider. A common approach used by the native woodland herbs, including several species at Ordway, is to spread via horizontal roots or stems that sprout new stalks at intervals along their growing length. This strategy allows parent plants to spread offspring into new habitats right away, to spread into areas where seed germination might not be successful, and to support new sprouts via physical connections through the most vulnerable portion of their development. Compared with seed dispersal, however, vegetative spread is limited in terms of the distance from the parent that offspring can explore. Likely for this reason, plant species us-

ing it generally also produce seeds, often equipped with specialized features to exploit wind or animals for longer-distance dispersal. Because such plants must allocate limited resources across two strategies, they usually produce fewer seeds than big bang reproducers such as garlic mustard.

The balance between the net advantages of seed-only and mixed reproductive strategies is probably mediated by many environmental factors. An especially likely factor is *disturbance*, a broad term used by ecologists to indicate removal of living biomass or disruption of the physical elements of an ecosystem. Removal of biomass and exposure of bare soil by sources of disturbance can increase the advantages of seeds relative to vegetative spread. In recent decades, the deciduous forests of Minnesota—the ecosystem type most frequently subject to invasion by garlic mustard—have been exposed to an increasing frequency and variety of disturbances. Expanding human populations have removed large tracts of forest and dissected many of the remaining tracts with roads, trails, and railways. The expanding white-tailed deer populations mentioned above are denuding native forest herbs and shrubs and exposing soil with their tracks and their habit of foraging beneath leaf litter. Outbreaks of disease such as Dutch elm and oak wilt, and parasites such as the emerald ash borer, are likely increasing rates of tree loss from canopy and subcanopy layers. And earthworms, introduced by European colonists to formerly glacier-scoured areas of the Midwest, are rapidly removing the deep litter and organic layers that historically blanketed the soils of the forest floor.

It seems likely that these disturbances have collectively tipped the balance toward favoring seed-based dispersal in forest understories. For a prolific seed-producer such as garlic mustard, that could amount to a significant boon.

Garlic Mustard Tags Along

The emerging picture of garlic mustard invasion as a complex result of multiple changes occurring in Midwestern forests is essentially the opposite of the causal scenario that seemed evident when the plant began to be studied intensively as an invader. Early on, it seemed likely the plant was spreading by something like brute force and driving undesirable changes in forest ecosystems in the process.

An increasing number of researchers view garlic mustard as a passenger of changes that are already happening.

Today, an increasing number of researchers view the plant mostly as a passenger of changes that are already happening. A deeper look through observation and experiment has revealed many factors that push back against the plant's most antagonistic traits, and has identified a suite of other likely reasons for its spread. If native ecosystems in garlic mustard's invaded range are sick, the plant is beginning to seem more like another symptom rather than the disease. Strikingly, many of the same people who initially sounded the alarm about garlic mustard have become the most strident champions of this updated view. Their public reversal is a textbook case of science working the way it is supposed to.

The willingness to update hypotheses in light of the best current evidence is one of the features that sets science apart as a uniquely reliable method of inquiry. In the case of invasion science, the quality of information generated by this approach holds many practical benefits in addition to theoretical ones. Understanding the actual causal relationships that underlie the correlation between garlic mustard spread and diminishing local diversity of native plants can help land managers avoid wasting limited resources on interventions that may be ineffective or even harmful.

Scientific understanding is far from perfect, of course. The updated view of garlic mustard comes with many caveats. The balance of factors aiding garlic mustard undoubtedly differs among sites, and competition or allelopathy may be important in some. It is also possible that garlic mustard will turn out to be a "backseat driver" that relies on environmental change to invade, but causes further harm to ecosystems once it arrives. This possibility is being studied by several groups, including ours. Whatever understanding we develop for garlic mustard will not directly apply to any other invasive species. Understanding causes and consequences is most reliable on a species-by-species basis. In the case of garlic mustard, for better or for worse, we may be the ones in the driver's seat.

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In Models We Trust—But First, Validate

Scientists use mathematical descriptions and simulations to make forecasts and provide recommendations to decision makers, but how reliable are these models?

Daniel Solow

All models are beautiful—even mathematical ones. They provide insights to scientists and to the general public about a vast array of phenomena in the real world, and we have come to rely on them much more than you may realize.

For example, to calculate trajectories of spacecraft, physicists use Isaac Newton's law of gravitation. To calculate the fair market value of a stock option, financial analysts use a model developed by Nobel Prize winners Robert Merton and Myron Scholes (and Fischer Black, who died before he could receive the Nobel). To decide whether to evacuate a city before a hurricane, local government officials consult the predictions of weather models.

All of these are mathematical models, even though we don't always refer to them as such. In physics, Newton's model and its like are usually described as "laws." If you're a trader on Wall Street, the Black–Scholes model might just be an app installed on your computer. Sometimes, predictions from models are extremely accurate—such as with Newton's model—and sometimes, not so much—such as models for predicting the outcome of a presidential election. How, then, should a member of the general public know when to trust a model's prediction?

All models are, by design, approximations of real-world phenomena. As such, they involve underlying assumptions—both explicit and implicit—together with numerical quantities whose values must be estimated and equations determined by the modeler. As the statistician George Box famously said, "All models are wrong, but some models are useful." For this reason, modelers should, when possible, give a good-faith estimate of how accurate their predictions are likely to be through a process known as *validation*. Even with the best available validation, there will always be some degree of uncertainty in predictions. In any case, it is crucial to have an understanding of how a particular model is validated—the more confidence you have in the validation, the more you can trust the resulting predictions.

The consumers of a model (that means you) should always approach it with healthy skepticism. The world is complicated, and every model has its limits. Most polling models predicted that Hillary Clinton would beat Donald Trump in the 2016 election. Naive epidemic models suggest that COVID-19 should have died out after its initial peak in April 2020. Who knows? Maybe by the end of this article, you'll agree with me that black holes (a prediction of a mathematical model) might not be black.

Getting the Ball Rolling

A *mathematical model* is a representation of a real-world phenomenon that uses mathematical concepts, symbols, and equations rather than, say, words or physical devices. Some models are *predictive*—meaning that they are used to forecast. Other models are *descriptive*—meaning that they are created to explain how a particular phenomenon or system behaves. Once properly validated, a descriptive model can sometimes be used to determine how the system can be improved, according to some performance measure. Alternatively, a descriptive model can be turned into a predictive model by seeing how the results would vary if certain changes are made in the model. In any case, all models—whether descriptive or predictive—should go through several cycles of validation and improvement.

In the late 1500s and early 1600s, Galileo Galilei developed a simple mathematical model to predict the motion of projectiles. Unlike Aristotle, who assumed that falling bodies approach a *constant speed*, Galileo argued that they increase their speed at a fixed rate. Today, we call this rate the *acceleration*, and denote it with the letter g.

Galileo's model can be expressed as a mathematical equation. If we drop a ball from a height d and measure when it lands, the distance traveled (d) should be related to the time of descent (t) by the following equation:

$$d = \tfrac{1}{2}gt^2.$$

In this model, g and t are *parameters* whose values, once determined, en-

QUICK TAKE

Mathematical models inform our understanding of the world. With varying degrees of success, they predict storm tracks, election results, and the motion of falling objects.

No model is perfect. Researchers who use mathematical models should question how they were validated, and what assumptions lie behind them.

Common validation methods include commonsense reality checks, comparison to experimental data, updating of parameters, confidence intervals, and sensitivity analysis.



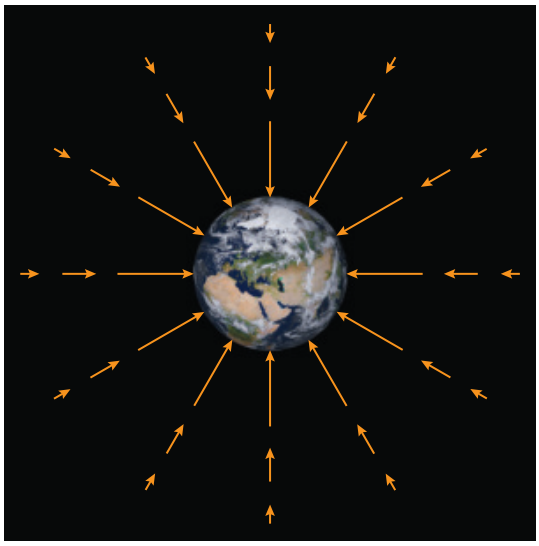
Museo Galileo, Firenze. Photo Franca Principe

In this 19th-century rendering of Galileo Galilei's inclined-plane experiment, a ball rolling down a chute will ring bells at equal time intervals. The apparatus visibly and audibly embodies Galileo's mathematical model, which predicts that the ball will travel increasing distances in equal time intervals. However, the model does not take into account the way that the gravitational field changes at large distances from Earth. Mathematical models can be highly reliable within the range of parameters in which they are validated, but can be highly unreliable outside that range.

able one to use the foregoing equation to predict the distance d traveled by the object. You might be able to test this prediction if you had a tall tower to drop a ball from, such as the Tower of Pisa (although there is no evidence that Galileo actually did so). But sometime around 1602, Galileo came up with the clever idea of rolling a ball down a gently sloping chute (*inclined plane*). The angle slowed the ball's motion and allowed for comparing experimental observations to predictions. "In such experiments, repeated a full hundred times," Galileo wrote, "we always found that the spaces traversed were to each other as the squares of the times" (which is exactly what the formula $d = \frac{1}{2}gt^2$ says).

Galileo's model has everything we could ask for: a theory, experimental confirmation, and successful prediction of new phenomena. Nevertheless, Galileo also made an instructive error. In his *Dialogue Concerning the Two Chief World Systems*, he used his model to compute that it would take 3 hours, 22 minutes, and 4 seconds for a ball dropped from the Moon's orbit to land on Earth. His estimates for the strength of gravity (g) and the distance to the Moon (d) were slightly incorrect, but those are minor issues, easily fixed. The real problem is more fundamental: His model assumed a constant gravitational acceleration. This assumption is quite accurate near Earth's surface, but highly inaccurate at astronomical distances. At the Moon, Earth's gravitational field is 3,600 times weaker than it is at Earth's surface. A ball dropped from the Moon's orbit would actually take more than four days to fall to Earth.

This example illustrates two concerns when using mathematical models: Galileo extrapolated his model beyond a regime where he had experimental data, and he failed to consider whether the assumptions behind the model still held in the new regime. In my opinion, physicists to this day continue to extrapolate more aggressively than modelers in other disciplines. Once a model is verified over a fairly large range of values of the parameters, most physicists presume that the theory is accurate over all values of the parameters, unless proven otherwise. By contrast, modelers in other disciplines tend to extrapolate less freely, and presume their model is not accurate until proven otherwise. Whether rightly or wrongly, physicists tend to believe that they are discovering universal truths, a belief that is evidenced by the use of words like "theory" or "law" rather than "model." This belief is often justified by validation over many values of the parameters, but it carries the risk of overextrapolation, that is, assuming that the model is correct for all values of the parameters.



Daniel Solow, Dana Mackenzie, Barbara Aulicino

Isaac Newton's inverse square law of gravity corrects a flawed assumption in Galileo's model. On astronomical scales, the gravitational force varies considerably. Here, the length of the arrows represents the strength of the gravitational force, which is constant at Earth's surface but decreases with increasing distance from Earth.

In Galileo's case, the correction came slightly less than a century later, when Newton formulated his universal law of gravitation:

$$F = GMm/r^2.$$

Again, this mathematical model is beautifully simple. It states that the gravitational force (F) between two objects, one of mass M and the other of mass m, is directly proportional to their masses and inversely proportional to the square of their distance (r). The constant of proportionality, G, is a parameter that physicists believe to be constant throughout the universe. (Hence, "universal law.") Newton's model explains why Earth's gravity is 3,600 ($=60\times60$) times weaker at the distance of the Moon ($r=60$ Earth radii) than it is at Earth's surface (where $r=1$ Earth radius).

Why should we believe Newton's model, and why did his contemporaries believe it? After all, it took three more centuries before we could get far enough from Earth to test it by direct experiment.

One reason is that Newton's model passed a set of three very stringent empirical tests, known as Kepler's laws. Any acceptable theory of gravity would have to be consistent with Kepler's observation that planets orbit the Sun in ellipses, rather than circles. It would also have to predict correctly their orbital periods and their variation in speed within an orbit. Newton was not the first physicist to theorize that gravity followed an inverse-square law, but he was the first to prove mathematically that the inverse-square law necessarily leads to elliptical orbits. This was the really decisive piece of evidence in his lifetime. Further evidence continued to accumulate as scientists used Newton's model to predict the motion of comets, to discover a new planet (Neptune), and finally to guide spacecraft to the Moon. Surely, no one could doubt this model any longer?

I'll leave you to ponder this question while we take a look at some other models and discuss how models can earn our confidence through validation.

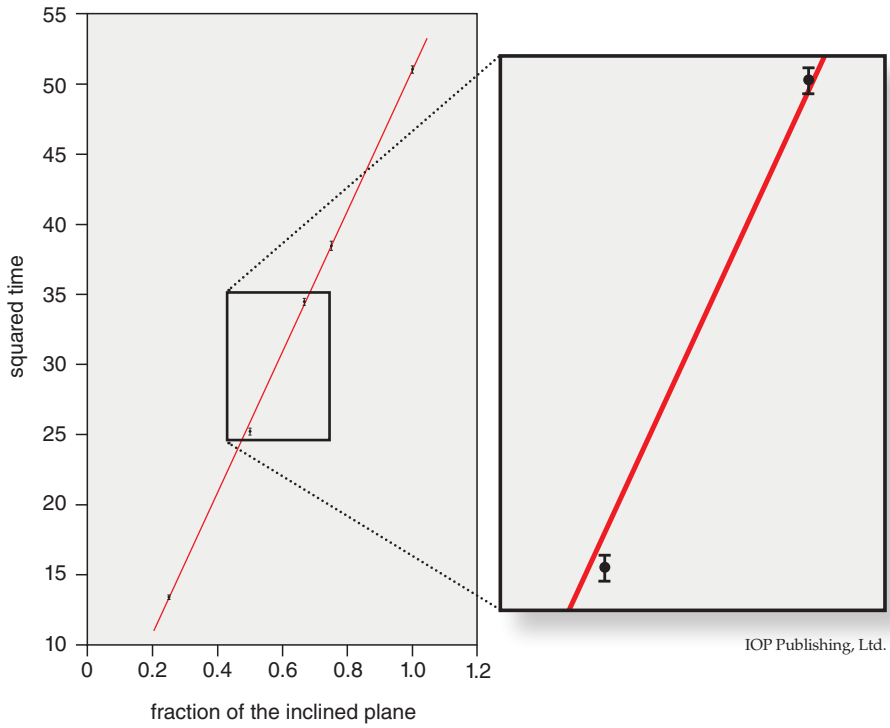
Reasons to Believe

As the examples of Galileo and Newton show, the most straightforward way to validate a model is to compare actual values of the quantities of interest to those predicted by the model. In many cases, differences between predicted and observed values can be used to *update* the model—that is, to adjust the values of the model's parameters in the hope of improving future predictions.

To compare observed to predicted values, we need to wait for the event to occur. But in many applications, we do not have that luxury. For example, when a hurricane threatens a community, government leaders need to decide now whom to evacuate, not after the hurricane has passed.

For certain types of models, it is possible to build in a measure of the expected accuracy of the resulting predictions, in advance of the actual event. One example of such a measure is called a *confidence interval*, which is a form of validation that provides a measure of how accurate the predictions are likely to be, and hence how much you should trust them.

For example, a week before the 2016 U.S. presidential election, an NBC



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One way to assess the reliability of a model is to state a confidence interval that indicates the likely amount of uncertainty. Here, data from a modern-day reenactment of Galileo's inclined-plane experiment are plotted, showing the squared time as a function of the distance traveled. The relation is very nearly linear, but the small vertical bars indicate the amount of uncertainty in the data. These are 68 percent confidence intervals, so it is not too surprising that one of the five confidence intervals actually misses the best-fitting line (*red*).

News/SurveyMonkey poll, based on a sample (which is a "model" of the population of all voters), predicted that Clinton would garner 51 percent of the popular vote, while Trump would get only 44 percent, with a predicted margin of error of 1 percent. In reality, Clinton got 48.2 percent and Trump got 46.1 percent. How could their prediction have been so wrong, and what does that 1 percent mean, anyway?

I'll answer the second question first. The margin of error of 1 percent means that the polling organization did not expect Clinton to get exactly 51 percent of the vote, but rather that it was "quite likely" that she would get between $51-1=50$ percent and $51+1=52$ percent. Thus, the confidence interval was from 50 to 52 percent. The polling organization would have expected the true percentage of Clinton's supporters to lie within that stated confidence interval, some large fraction (often 95 percent) of the time.

One possible answer to the first question—but certainly not the only answer—is that in order for a prediction from a sample to be accurate, the sample should be "random." But pollsters have learned through painful experience that drawing a truly random sample is impossible. After the 2016 election, many polling organizations learned that their samples had not adequately taken into account white voters with a high school degree or less, a demographic group that does not participate enthusiastically in polls and that voted heavily for Trump. Historically, this group of voters had not made a significant difference in previous elections, but it sure did in 2016.

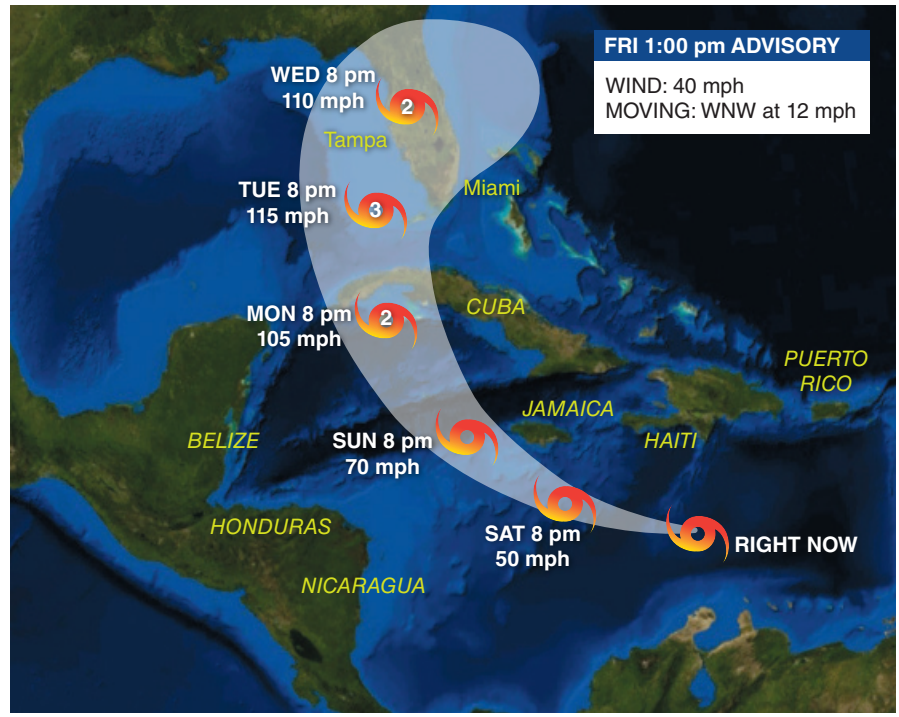
The foregoing example shows that confidence intervals, too, are subject to uncertainty and can be misleading or even invalid. Because polling in the 2016 election was inherently inaccurate due to having used a sample that excluded a large and important group of voters, the corresponding confidence interval was also inaccurate to the point of being misleading. Although confidence intervals are, in most cases, helpful, they are also subject to inaccuracies and, in extreme cases such as the 2016 polls, can lose their value entirely. Nevertheless, if properly validated by avoiding systemic errors, confidence intervals are a form of validation that can indicate the level of trust you should have in a model's predictions.

You may also wonder why the pollsters didn't save themselves some embarrassment by giving a 100 percent confidence interval, so that they could be absolutely certain that their estimate would capture the correct value of the quantity of interest. Unfortunately, the only statement they could make with 100 percent confidence was that Clinton would get between 0 and 100 percent of the vote. This statement is highly accurate, but completely useless. In general, the more confident you want to be, the more you have to "pay" for it with a wide confidence interval.

In the foregoing example, the model merely had to make a prediction of two values—the fractions of voters who would cast their votes for Clinton or for Trump. For a hurricane, modelers have to predict an infinite number of values—namely, the path that the eye of the hurricane will follow. In this case, the "confidence interval" is actually a *cone of uncertainty*. This cone is typically estimated by generating an ensemble of possible forecasts—very much like polling voters! (And like elections, hurricanes sometimes defy the model's prediction entirely.)

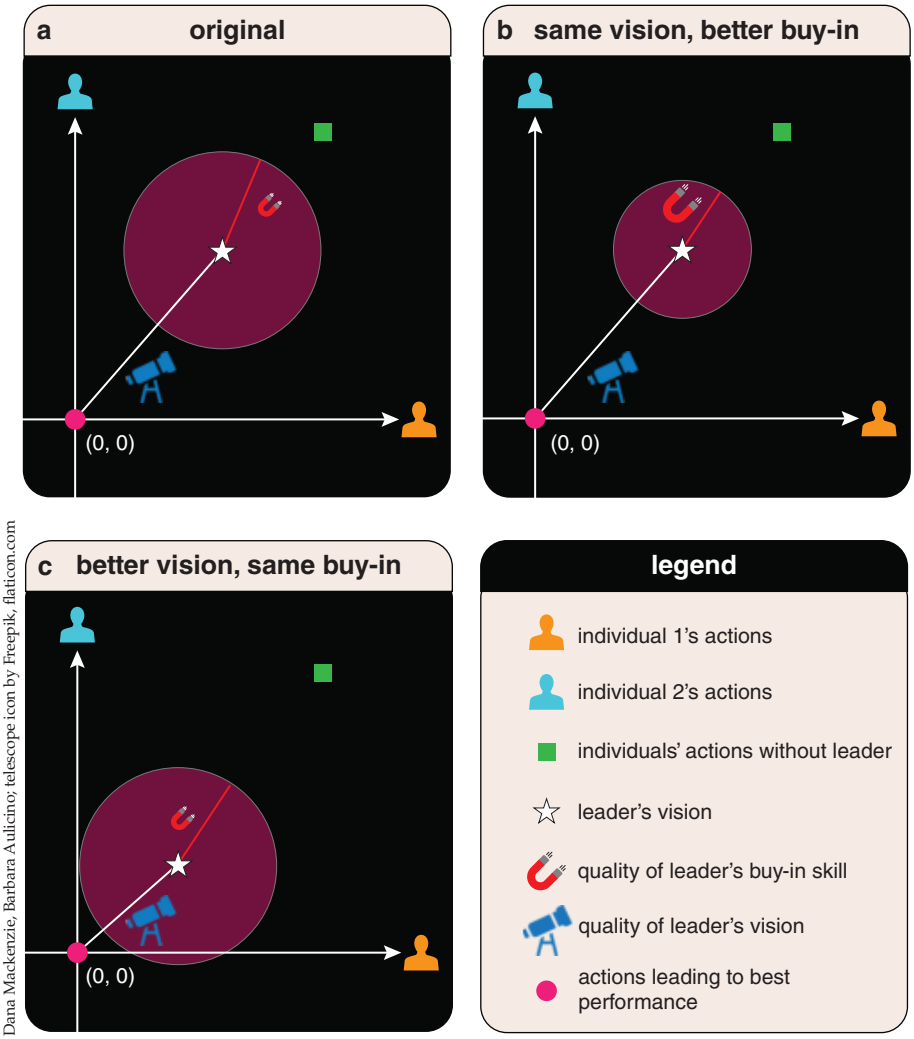
The consumers of a model should always approach it with healthy skepticism. The world is complicated, and every model has its limits.

Another popular kind of model is a *regression model*. In such a model, the variable whose value you wish to predict, say Y, is believed to depend on another variable, say X, through a mathematical relationship. A value for X, once determined, is then used to predict the value of Y. In other words, the unknown value of Y "regresses" to the known value of X via the mathematical relationship between X and Y. As with all models, a regression model requires



Barbara Aulicino, Wikimedia Commons/NASA WorldWind Globe

A familiar example of a confidence interval is a projected hurricane track, as shown in this map of Hurricane Ian from 2022. The width of the track widens as the projections move farther into the future, which indicates greater uncertainty about the storm's path, not necessarily an increase in the size or severity of the storm.



Dana Mackenzie, Barbara Aulicino; telescope icon by Freepik, flaticon.com

In this mathematical model of leadership, created by the author, for a hypothetical organization with one leader and two employees (or "individuals"), the white star indicates the leader's vision for actions that individuals in the organization should take, and the pink circle represents the leader's charismatic skills. A smaller disk means the leader is more effective at persuading people to buy into their vision.

validation, which researchers have been able to do using confidence intervals.

For a concrete example, let's go back to Galileo's inclined-plane experiment. Although his original data are unavailable, Samuele Straulino of the University of Florence in Italy has reproduced the experiment, down to Galileo's use of a water clock, and I will refer to Straulino's data. If we plot the time squared (t^2) against the distance (d) traveled, we see approximately a straight line. In fact, as shown in red in the graph on page 44, Straulino's data seem to be quite a good fit to the regression line $t^2 = 50.3d + 0.7$, shown in red (the mathematical equation relating $Y = t^2$ to $X = d$).

Even though the fit is extremely good, it is not perfect. Straulino repeated the experiment 30 times, for each of Galileo's reported distances ($d = 0.25$, 0.5, 0.67, 0.75, and 1, expressed as fractions of the length of the full chute). The times of descent are not the same every time, but vary over a range of values due to experimental error.

Straulino, as a good modern scientist should, represents the experimental uncertainty by a small vertical bar: the 68 percent confidence interval for each time measurement. Galileo simply said "we always found" that time squared was proportional to distance. But Straulino didn't always find that. For example, his confidence interval for $d = 0.5$ (the second bar from the left) completely undershot the expected value. Modern scientists would convey the uncertainty something like this:

$$t^2 = (50.3 \pm 0.6)d + (0.7 \pm 0.4).$$

Here, the values after the plus-or-minus signs give a confidence interval for the parameters 50.3 and 0.7, respectively. For the science consumer, the most important lesson is that admission of uncertainty in a mathematical model is a virtue, not a deficiency. Predictions from a model that do not come with an estimate of uncertainty should be viewed with caution.

My Own Modeling Adventure

Physicists and weather forecasters are lucky in the sense that they have ample data with which to validate their models. Others are not so lucky—it can often be challenging, if not impossible, to obtain real-world data. How, then, can one validate such a model? At the very least, one should use *commonsense validation* to confirm that predictions from the model make common sense.

Being a professor in a school of management, I became interested a few years ago in understanding two different kinds of leadership skills. One, which I call *visionary* skill, is the ability of a leader to identify a good target for the organization to aim for. The second, which I call *charismatic* skill, is the ability to modify other people's behavior to get them to buy into the leader's vision. I set out to see if I could build a model to gain insights into the trade-offs between a leader's visionary and charismatic skills.

For the sake of the model, I assumed that each person in the organization takes an action, which I represented by an arbitrary number. The first person chooses the number x_1; the second person chooses the number x_2, and so on. The collective actions of everybody in the organization can be identified by the list $(x_1, x_2, \ldots)$. For simplicity, I will illustrate the model in an organization with only two people, so you can visualize the two actions (x_1, x_2) as a point in a plane. But the model can easily be extended to organizations with any number of people.

Next, I needed a way of assessing the organization's performance based on the collective actions. Thus, I supposed that there is a performance function, $f(x_1, x_2)$, that associates with each pair of actions (x_1, x_2), how well the organization performs, on a scale of 0 to 100, with 100 being the best. There are some actions that result in the best possible performance of the organization; so, again for simplicity, I supposed that those best actions are in the center of

the plane, at (0, 0). Note that nobody actually knows the best actions; that information is only available to me, as the creator of this particular model.

Now, suppose that a leader is introduced. In the model, the leader can decide what actions she thinks everybody should take to achieve the best organizational performance. Suppose she believes the first individual should take action z_1 and the second should take action z_2; we can call the list (z_1, z_2) her *vision*. A good visionary leader will choose a vision that is close to the ideal point (0, 0). (But remember, the leader is not a god, so she doesn't know that.)

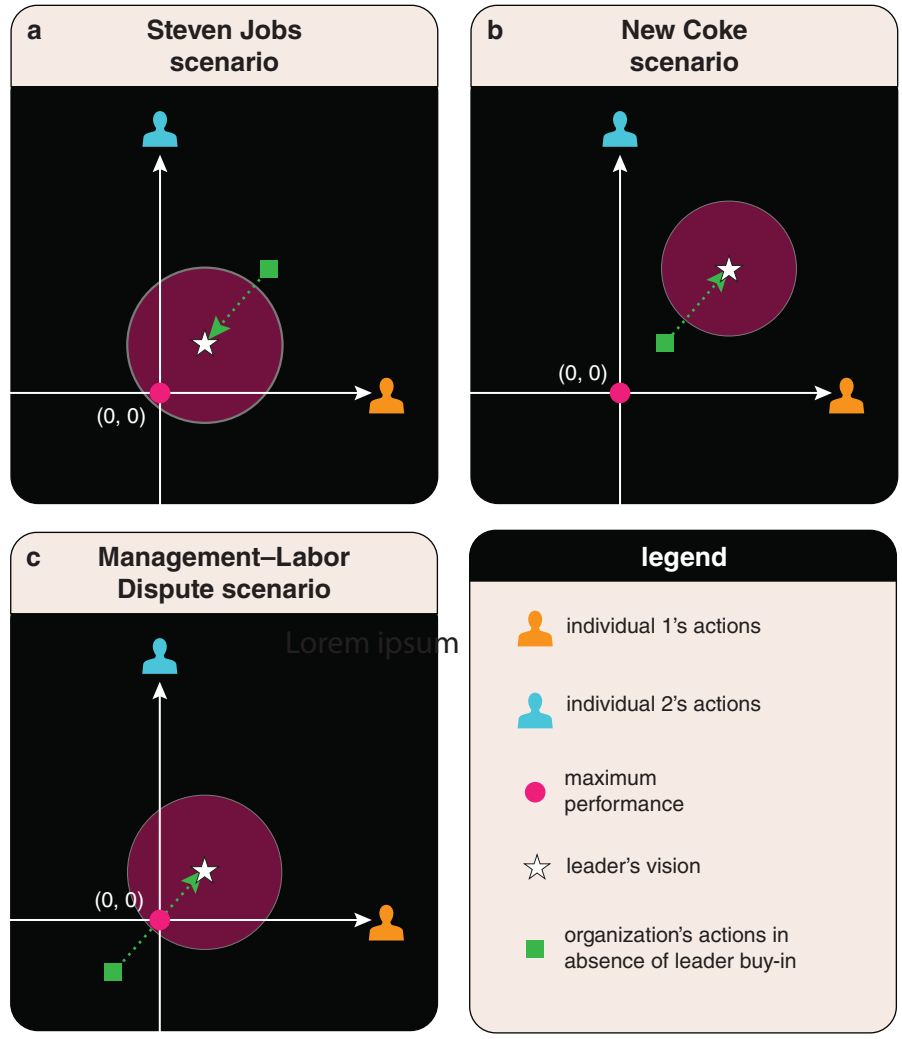
Finally, the leader has to influence other people's actions by creating buy-in. To model this ability, I imagined a "charisma ball," that is, a circle of radius r centered on the leader's vision (z_1, z_2). I posited that everyone in the organization would then choose an action at random within this ball. The smaller the ball, the more effective the leader is at persuading (or coercing!) others to buy into her vision.

I would be the first person to admit that this model is in no way realistic. Furthermore, it is not possible to validate the model by comparing forecasts to actual results, because there is no easy way to measure a leader's visionary and charismatic skill. So, how can one trust predictions from this model? Although models do not necessarily have to be realistic, they do have to produce predictions that make sense.

To illustrate this commonsense validation, it is easy to show that the model predicts that a great visionary leader with no charismatic skill is ineffective. If the leader has no charisma, the charisma ball in the model will be infinitely large; people will just go on with whatever actions they would have taken anyway, and the performance of the organization will not change . . . and this makes sense.

Unfortunately, however, the model I just described ran into a problem. It predicted that, for a fixed vision, a more charismatic leader is *always* better for the organization than a less charismatic leader. This outcome is clearly not true in the real world! The fact that the model made a prediction that does not make common sense is a form of validation that indicates the model is not valid and needs to be corrected, if possible.

Now is when the art of mathematical modeling begins. I had an initial model that was too simple, and it made an inaccurate prediction. It's important to start as simple as possible so as to be able to understand what goes wrong and make appropriate adjustments. In this case, I found a small refinement that not only avoided the more-charisma-is-better fallacy, but also led to other commonsense predictions for several familiar organizational scenarios. In the "Steven Jobs" scenario, a visionary leader improves the organization's performance steadily as buy-in improves. In the "Out-with-the-Old-Coke" scenario, the leader has a poor vision and the organization does worse as the leader becomes more effective at creating buy-in. Finally, a very interesting intermediate scenario could be called the "management–labor dispute," where a small amount of buy-in improves the organization's performance, but a large amount of buy-in (possibly enforced by management) is detrimental.



This improved version of the author's model reproduces three common organizational scenarios: a leader whose organization performs better and better as charismatic skill improves (that is, as the disk shrinks, *a*), a leader whose organization performs worse and worse as the charisma disk shrinks (*b*), and a leader whose organization first performs better, then performs worse as the charisma disk shrinks (*c*).

My leadership model still has a long way to go, but through commonsense validation, the model has reached the stage where it begins to create reasonable predictions that lead to understanding.

Are Black Holes Really Black?

Now, let's return to Newton's gravitational model, which has been validated experimentally for many values of a mass m that is a distance r from a gravitating mass M. This model has been proven to be remarkably accurate for many values of m, M, and r. But is the model valid over all values of these three parameters? Is the model valid when the underlying assumptions do

not hold? There is always room for more validation.

One basic assumption of Newton's model is that the bodies M and m are point masses, or spherically symmetrical. This assumption is not true for real planets, such as Earth. As a satellite flies over a mountain range, it will feel an excess gravitational pull from that range; flying over the ocean, it will feel a deficit. These effects are extremely small, but they are detectable by a sufficiently sensitive satellite. A project called the Gravity Recovery and Climate Experiment (GRACE) made a mathematical model of Earth's gravitational field in the early 2000s. It is fascinating to see the lumps and bumps in Earth's gravitational field: For example, you can see a mountain range in the middle of the Atlantic Ocean! (For geology buffs, it's the Mid-Atlantic Ridge.) Also, the gravitational anomalies change over time due to, for example, the melting of glaciers. Thus, one can use the GRACE model—but not Newton's model—to monitor climate change.

Another assumption of Newton's model is more deeply hidden, and it took the genius of Albert Einstein to question it. Newton assumed that gravity is a force that acts instantaneously through space. Einstein, on the other hand, had the amazing insight that objects, such as planets and stars, warp the space (and time) around them, and this warping—called *curved spacetime*—is what we perceive as "gravity." In 1915, he created a mathematical model, in the form of 10 nonlinear second-order partial differential equations, called the *Einstein field equations*, that describe both the effect of matter on spacetime and the effect of curved spacetime on matter, leading him to the conclusion that gravity is not a force and does not act instantaneously through spacetime.

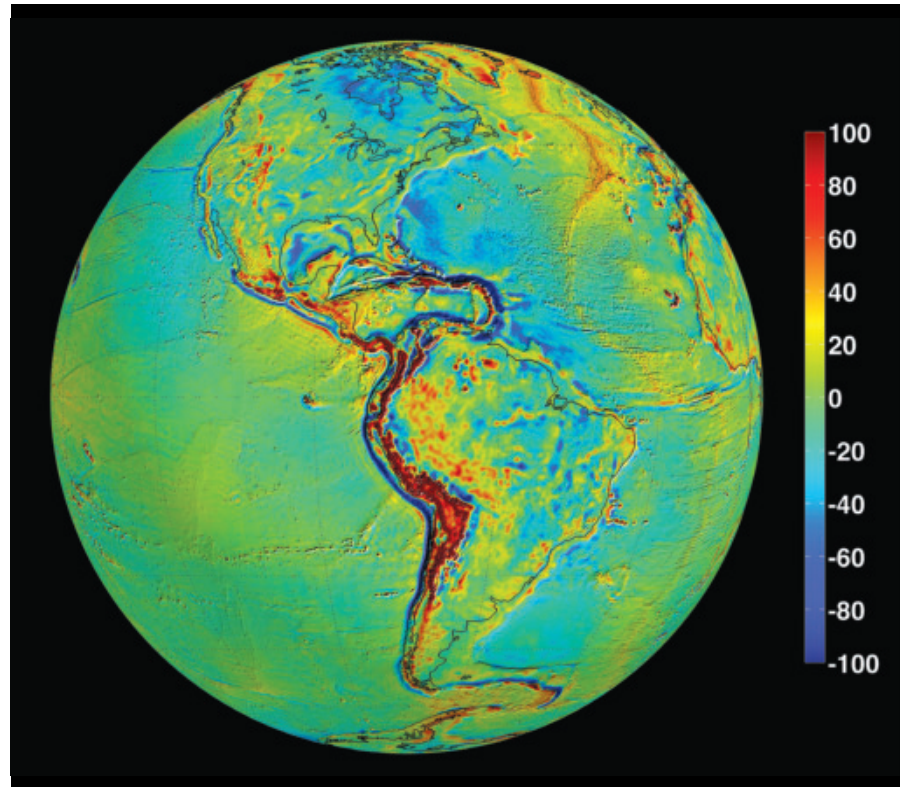
Some of the predictions of Einstein's model were confirmed early on. His theory accounted for a puzzling acceleration in Mercury's orbit that causes it to "precess" like a top—which Newton's model was unable to account for. Much more dramatically, his theory predicted that light rays from distant stars would bend around the Sun, ever so slightly, due to the curvature of spacetime. No one had ever observed this phenomenon before, and it was confirmed for the first time (including the correct amount of bending) in the total solar eclipse of 1919.

For the science consumer, the most important lesson is that admission of uncertainty in a mathematical model is a virtue, not a deficiency.

A much more subtle prediction of Einstein's model was discovered as a result of work done in 1915 by a young German physicist named Karl Schwarzschild, who tragically died only a year later on the front lines in World War I. I mentioned above that Einstein framed his theory as a set of differential equations. Unfortunately, these equations are so complicated that very few exact solutions of them are known. And in Einstein's day, computers powerful enough to derive approximate solutions did not yet exist.

The *Schwarzschild metric*, as it is now known, was the first exact solution ever found. Not surprisingly, it is the simplest possible case, describing a spherically symmetric universe with one star in it. The Schwarzschild metric predicts that if this star is massive enough, it can warp spacetime so much that light cannot escape. It is Einstein's light-bending effect on steroids. If you should (unluckily) wander too close to the star and try to send out a distress signal, no one would receive that signal—your light beam could not escape. As a result, these stars became much better known by the colloquial name of *black holes*.

The Schwarzschild metric has resulted in a number of other predictions that have been verified to a high degree of accuracy. As a result, the existence of black holes is now ac-



NASA/JPL/Caltech

Newton's inverse-square law assumes that Earth is spherically symmetric, which is false: Earth has ocean basins and mountain ranges. These geological forms produce deviations in the gravitational field on the order of 100 parts per million. The mathematical model shown here was derived from data from the GRACE (Gravity Recovery and Climate Experiment) satellite mission.

cepted as a reality. However, real black holes are not described perfectly by the Schwarzschild metric: A star is not spherically symmetric, other stars do exist, and, who knows, maybe Einstein's field equations are not 100 percent accurate—after all, all models are wrong, but some are useful. So it is reasonable to ask: Should one believe that light does not escape a black hole? Just because general relativity has been validated for many values of the parameters, does that mean that the theory is valid over *all* values of the parameters, including those associated with a black hole, for which experimental data are not available?

This brings us to our last technique modelers have developed for validating mathematical models, called *sensitivity analysis*. When we recognize that predictions depend on the values of the parameters, we can ask how the predictions would change if the value of one (or more) parameters is tweaked. If a relatively large change in the value of a parameter has little effect on the prediction, then one can feel confident that the value of the parameter that was used for the prediction is fairly reliable. On the other hand, if a small change in the value of a parameter results in a big change in the prediction, then we had better make sure that the value of that parameter used in the prediction is really accurate.

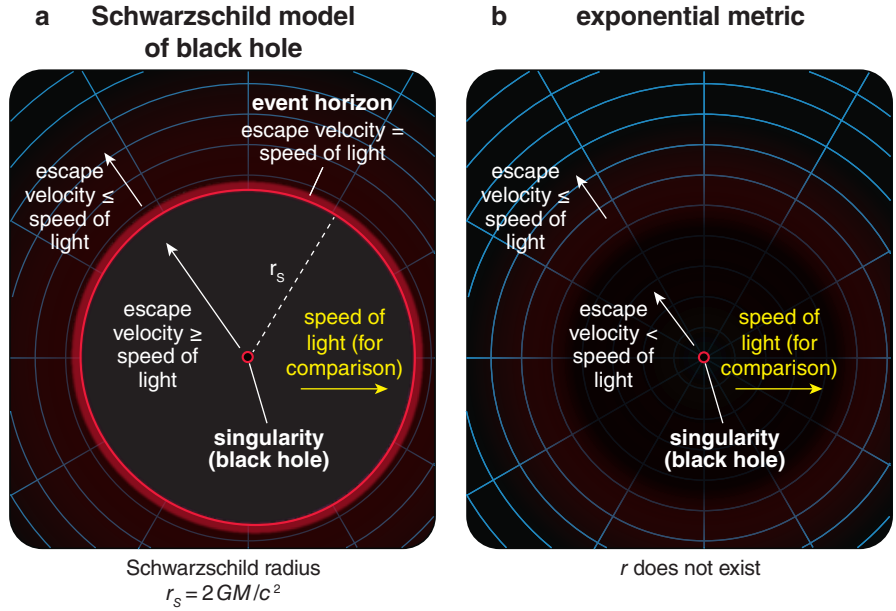
In the case of the Schwarzschild metric, a key prediction for a black hole is the *event horizon*, the "point of no return" inside of which light cannot escape. In both the Newton and Schwarzschild models, the escape velocity for any object at distance r from a star of mass M is $v = \sqrt{2GM/r}$. This equation tells you the minimum velocity (v) that a rocket needs to achieve in order to escape the star's gravitational field. If the rocket is at a distance $r_S = 2GM/c^2$ from the black hole (where c denotes the speed of light), we find that the escape velocity v is exactly c. At any distance less than r_S (the "Schwarzschild radius"), the escape velocity will be greater than c, and so no light can escape.

How sensitive is this conclusion to small changes in the metric? When I learned of this formula for the event horizon, I created my own slight change in the metric to see what would happen. While the "exponential metric" I considered was not an exact solution to Einstein's field equations, it produced a new formula for the escape velocity that, *for all values of* M *and* r, *is less than the speed of light*. Thus, light always escapes from a "black hole" with this metric! (I learned later that the Turkish physicist Hüseyin Yılmaz had discovered this exponential metric 60 years earlier by modifying Einstein's field equations.)

Should we believe the exponential metric model? Matt Visser, a mathematician at Victoria University of Wellington, New Zealand, points out that it is completely consistent with Einstein's equations, provided that one assumes the existence of a massless "ghost" field with negative kinetic energy. It is exotic physics, but in recent years we have seen other exotic physics become widely accepted. (Think of dark matter.)

If, in fact, light does escape from a black hole, one can ask why we do not detect it. One reasonable explanation is that the gravity of the black hole weakens the light to such an extent that our detectors—located thousands of light-years away—cannot register the tiny light leak.

In any case, sensitivity analysis shows us that a very small change in the Schwarzschild metric leads to a dramatic change in the prediction of light not escaping a black hole, and this should at least raise a yellow caution flag. Some modelers might wish to reserve judgment on whether black holes are, in fact, black.



These two diagrams illustrate variations on sensitivity testing for the Schwarzschild model of a black hole, including the original model with an event horizon (*a*). The exponential metric is a mathematically small change to the Schwarzschild model that nevertheless has a large effect: The event horizon completely disappears (*b*).

In summary, mathematical models can provide understanding of real-world phenomena and make predictions that are highly valued. However, one must keep in mind that all models are wrong, but some are useful. Models might be wrong because the values or their parameters are not known exactly and have to be estimated, or because some of the underlying assumptions might be incorrect or not hold for all values of the parameters. This uncertainty means that every model needs to be validated so as to provide a degree of trust in the resulting predictions. A model can be validated by comparing predictions to experimental observations, by noting the model's track record, by including confidence intervals, by sensitivity analysis, or at the very least by establishing that predictions make common sense. Regardless of the amount of validation, one must accept some degree of uncertainty with model predictions, so some amount of skepticism is always warranted. The more you know about how a model is validated, the better you can decide how much to trust its predictions.

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A Deep Dive into Innovation

Groundbreaking innovations may appear to be strokes of genius, but they are most often the product of context, consequence, and coincidence.

Edward A. Wasserman

As you watch Michael Phelps swim the butterfly stroke, you marvel at the amazing coordination of his muscular arms, legs, and torso. These powerful motions seem to have been perfectly planned to outpace his rivals in what is the most demanding of all swimming strokes. What you may not appreciate is that the butterfly stroke was never planned. Nor, for decades following its debut, was it even an approved stroke in the Olympic Games.

Because of its striking suitability to specific situations, the butterfly stroke may appear to have been ingeniously and foresightedly designed. More often than not, however, this and many other creative acts actually arose "as if by design." A deep dive into the history of this innovation provides a firmer grasp on the very nature of behavioral creativity. What emerges is an intricate web of causation involving three main factors: context, consequence, and coincidence.

By concentrating on the process rather than the product of innovation, behavior emerges as the very center of creative human endeavor—for it is truly behavior that produces the innumerable innovations that have captivated thinkers' imaginations. Those most splendid theories, goods, gadgets—and swimming strokes—would never have come into being without the behaviors of their inventors.

We admittedly remain far from fully understanding how creative behaviors originate and evolve. But I firmly believe that we'll gain ground far faster by abandoning fruitless fictions such as genius and insight, and by focusing instead on what can be observed and investigated.

As If by Design

Genius. Inspiration. Insight. Foresight. Without deeper inquiry, most people blithely accept that these are the dominant forces that foster game-changing innovations by highly celebrated heroes. That's largely because it's all too easy to tell tall tales without doing the hard work of exploring the factors that actually participate in advancing the human condition.

But, the insightful or eureka moment is a myth: an altogether naive and fanciful account of human progress. Innovations actually arise from an intricate web of historical, circumstantial, and adventitious influences.

However, don't be intimidated by such complex determinism: A simple law of behavior is actively at work in the creative process. The *law of effect* inescapably and mechanically strengthens actions that have succeeded in the past over actions that have either failed or been maladaptive. The law of effect knows no bounds. It operates in all realms of human endeavor: sports, the arts, politics, science, medicine, and technology.

Originally formulated in the late 19th century by American psychologist Edward Thorndike, the law of effect debunks the myth of creative genius and closely parallels Charles Darwin's theory of natural selection. Indeed, this "selectionist" law is every bit as controversial as Darwin's evolutionary theory.

From its naturalistic perspective, the law of effect asserts that the strongest creative forces lie outside rather than inside of us. Most pointedly, we don't deliberately, foresightedly, and intelligently design our own behavior; rather, our behavior is shaped by our own past history and by the unique circumstances in which we find ourselves. That behavioral shaping process is often a haphazard, trial and error affair with no obvious end in sight; yet it can generate innumerable innovations that significantly advance the human condition and deceive historians into incorrectly interpreting them as due to flashes of creative insight or foresightful design.

Creativity lies at the heart of all adaptive action. Although we rarely appreciate it, each of us innovates every day as we adjust to life's many trials. Large and small, those innovations enable us, as individuals and as a species, to thrive.

The law of effect generally promotes adaptive behavior, retaining successful actions and eliminating unsuccessful ones. Yet, this decidedly trial and error process is neither rational nor infallible. Whatever its limits and liabilities, the law of effect provides our best means of surviving in a harsh and uncertain world.

As a psychological scientist concerned with how both humans and animals adjust to the frequently changing demands of survival, I find it perfectly clear that the most creative of those behaviors have posed the greatest challenges to existing theories of learning and behavior.

QUICK TAKE

The idea of a lone creative genius is captivating, but it does not match the reality of the collaborative and incremental processes behind most innovations.

Creative behaviors develop in response to the environment and evolve over time. This *law of effect* holds true in all areas of human endeavor, from technology to sports.

The invention of the butterfly stroke provides a case study for how an action that might seem natural or obvious was in fact developed by many people through trial and error.



REUTERS/Alamy Stock Photo

Michael Phelps (shown here in the London 2012 Summer Olympic Games 100-meter butterfly semifinal, in which he went on to win gold) has disproportionately long arms and flexible ankles that are perfectly suited to swimming's most challenging stroke: the butterfly. The story of how this flashy swimming style developed from the more mellow breaststroke is an example of how context, consequence, and coincidence can result in behavioral innovation.

Behavioral innovation is often said to be overdetermined: Even singular effects can be determined by multiple causes. Those causes can be boiled down to context, consequence, and coincidence. These three C's may each participate in behavioral innovations, but to varying degrees in any individual instance: One size most assuredly doesn't fit all.

Everything happens at a particular time and in a particular place: its context. This overall setting is frequently referred to as the prevailing *zeitgeist*—the defining character of a particular period of history as shown by the ideas and beliefs of the period. But, that context is usually much more limited when we consider the circumstances in which individuals find themselves. Furthermore, individuals have their own personal experiences that they bring to the historical moment. Laboratory research tries to minimize such conspicuous idiosyncrasies, but history celebrates and respects the context of creation.

Novel behaviors must have consequences if they are to take hold. The odds are decidedly against the strengthening of novel behaviors. Take the analogy of the forward pass in football. Two out of the three possible things that can result are unfavorable: an incompletion or an interception. Only the completed pass is a favorable outcome. The same goes for novel behaviors. Nothing good or something bad is likely to follow. Only a good outcome will reinforce a novel behavior. It's no wonder then that, under stable conditions, people respond in highly regular ways. It's only when uncommon circumstances arise that routine responses falter and novel actions emerge.

Finally, chance may bring people and possibilities together. Good fortune is what comes from taking full advantage of those possibilities. Of course, you can't plan on luck to get you out of a jam. Nevertheless, opportunities can arise from adversities. And, when they do, exploiting them makes the proverbial lemonade out of lemons.

Components of the Butterfly

Phelps is arguably the greatest Olympic athlete of all time. He is unarguably the most decorated. Over the course of his extraordinary five-game Olympic swimming career, Phelps earned a total of 28 medals: 23 gold, 3 silver, and 2 bronze. The butterfly was his signature stroke. In this particularly demanding event, Phelps individually earned six gold and two silver medals in the 100- and 200-meter races.

Those unfamiliar with the butterfly stroke are sure to find it baffling. The windmill motion of both arms, first flung upward and forward out of the water, and then thrust downward and backward into the water, coupled with the rhythmically undulating torso and powerful leg kicks, create a seemingly chaotic concatenation of strenuous bodily maneuvers. Perhaps because the butterfly has been called the most aggressively athletic of all swimming strokes, it's rumored to be Russian President Vladimir Putin's favorite, thereby flaunting his manliness.

No less baffling than the stroke's peculiarity is its origin. As with most origin stories, the history of the butterfly stroke is a rather frustrating evolutionary tale to tell. The patchy story line involves a host of disconnected contributors, anecdotes of dubious authenticity,



Edward A. Wasserman

This bronze relief sculpture by artist Larry Nowlan commemorates University of Iowa swimmer Jack Sieg's contributions to the invention of the butterfly stroke. In the 1930s, Sieg and coach David Armbruster combined an over-the-water arm stroke with a dolphin leg kick to create a new stroke that was faster and more exciting to watch than the breaststroke.

and a wealth of unresolved controversies. Further contributing to the story's complexity is the fact that the two main elements of today's butterfly stroke—the flying or over-the-water arm stroke and the fish-tail or dolphin leg kick—are historically unrelated. Finally, there is the fact that the full butterfly stroke did not suddenly emerge; it gradually grew out of the already familiar, but far less flamboyant, breaststroke.

As far as the double over-the-water arm stroke is concerned, many writers credit its invention to Sydney Cavill. This Australian swimmer emigrated to the United States in the early 1900s, where he coached several competitors at San Francisco's Olympic Club. Also adopting the over-the-water arm stroke was German swimmer Erich Rademacher, who competed in the United States in 1926 and 1927, as well as in the 1928 Olympic Games in Amsterdam, the Netherlands. In some of these breaststroke events, Rademacher has been claimed to have incorporated a single over-the-water arm stroke as he approached the turns and at the end of the race. Occasional use of the over-the-water or "fly-away" technique is also credited to the Spence brothers, Wallace and Walter, both of whom trained and coached at the Brooklyn YMCA.

However, most often discussed in connection with the fly-away arm stroke is American swimmer Henry Myers of Brooklyn's St. George Dragon Swim Club. Myers used the fly-away stroke for the entire breaststroke leg of a three-stroke medley race at a 1933 YMCA competition in Brooklyn. His success in that race and in later events convinced Myers—and his competitors—that this innovation could greatly enhance swimmers' breaststroke speeds. Myers also perceptively suspected that this double arm motion might inspire much greater interest in this aquatic event, as even he found it rather unexciting to watch a breaststroke race. Adding the fly-away—with its spectacular splashing and violent arm motion—to the breaststroke might be more likely to spark fan fervor.

Other authors have been intrigued by the possible role that American Volney C. Wilson played in developing the underwater dolphin kick. Wilson is said to have explored its possibilities before beginning work on nuclear fission and the atomic bomb in the Manhattan Project. Wilson was a strong swimmer and an alternate on the 1932 Olympic water polo team, who was allegedly inspired to explore this technique by his informal studies of fish propulsion at Chicago's Shedd Aquarium.

Putting It All Together

All of that colorful history notwithstanding, the full realization of the dolphin kick and its successful integration with the over-the-water arm stroke is truly an Iowa story. The first public notice of Iowa's contribution to this evolutionary tale came in the August 1936 issue of *Esquire* magazine. In "Frog, Butterfly and Dolphin," G. Clifford Larcom, Jr., teased readers with a titillating subtitle: "Traditional strokes go the way of bloomer bathing suits as the engineers revise swimming." He then proceeded to describe several current developments in swimming techniques. Most noteworthy among these developments were the dramatic modifications then underway in the breaststroke:

> The latest breast stroke creation, a muscle devastating affair, is the dolphin stroke, modelled by Jack G. Sieg and tailored by Coach David A. Armbruster, both of the University of Iowa. Mr. Armbruster's coach's eye was caught one day by the sight of young Mr. Sieg rushing along under water with no other means of propulsion than the undulating, wriggling motion of a fish. Alert Mr. Armbruster incorporated this type [of] kick with the double overarm and the results were sensational for the good old breast stroke. . . .
>
> The stroke completely junks the old breast stroke kick and eliminates the checking forces developed in the old method. . . . If sanctioned, it would correct the one factor that retards interest in the ordinary breast stroke—its slowness.

Contributing to the development of the butterfly stroke were the advanced facilities that were available to the University of Iowa swimmers. On October 25, 1925, the Iowa State Board of Education authorized construction of the world's largest fieldhouse, including the world's largest indoor pool. A 20-yard pool in the campus Armory was also available for conducting controlled swimming experiments. It provided facilities for underwater photography and motion picture recording. In and of themselves, those facilities might have given Iowa swimmers a modest edge in training. They might also have attracted some of the nation's best swimmers to the Iowa City campus. But, it was Iowa's famed coach that most surely contributed to swimming history.

David Alvin Armbruster, Sr., never participated in a competitive swimming race. Nevertheless, he was the University of Iowa's first swimming coach, serving for 42 years (1916–1958)

figure 1.

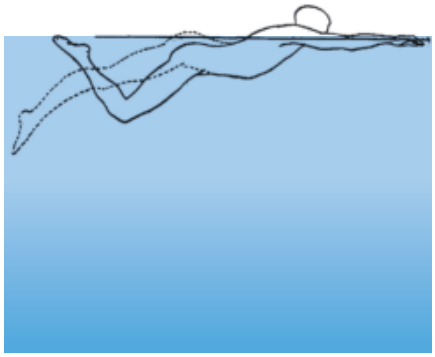


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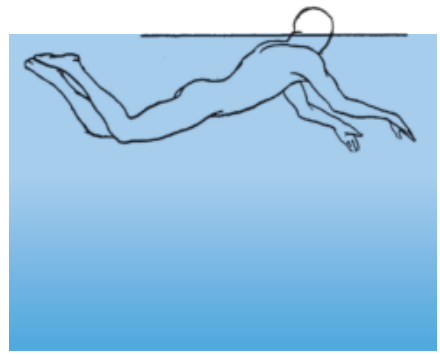


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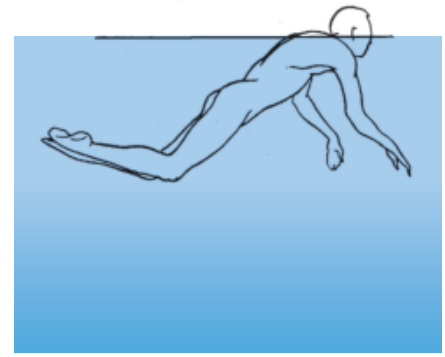


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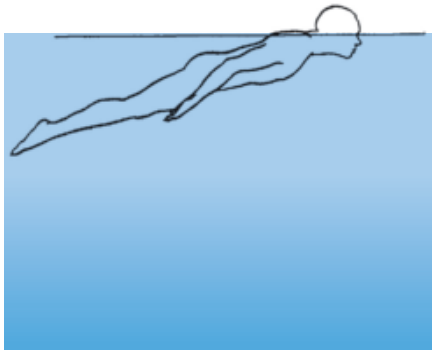
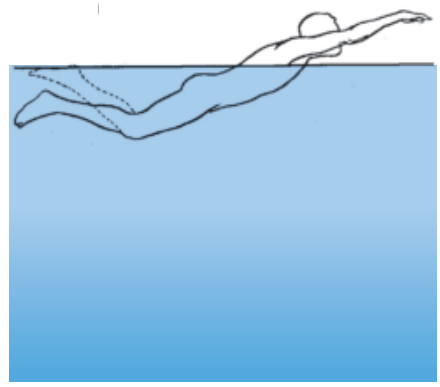


figure 5.



In a 1935 article, Armbruster and Sieg described their new "dolphin breast stroke" as resembling the more common freestyle stroke, but the arms and legs move in unison rather than alternating. The legs kick twice for every arm stroke, and that power propels the swimmer's torso and arms out of the water in the distinctive "flying" motion. These line drawings are adapted from diagrams that appeared in the original article and were based on observations of Sieg swimming at the University of Iowa.

and compiling over 100 all-American honors. He coached 14 National Collegiate Athletic Association (NCAA) champions as well as both gold medal (Wally Ris) and silver medal (Bowen Stassferth) winners in the Olympic Games. Nevertheless, he is perhaps most famously credited with inventing the butterfly stroke—the most recent swimming stroke for national and international competition, joining the freestyle, breaststroke, and backstroke—as well as originating the flip turn.

Armbruster was widely recognized as the scientific "dean" of competitive swimming from the 1930s through the 1950s. He earned that esteemed reputation because of his careful and detailed studies of swimmers' various techniques, stimulated in part by his colleague and occasional collaborator C. H. McCloy. America's first giant in the bioscience of physical education and exercise, McCloy was a staunch advocate of strength training (which Armbruster adamantly rejected for his swimmers, believing that it would make them "muscle bound").

At a 1911 swim carnival in Toronto, Armbruster saw George Corsan, Sr., (who went on to become one of his early instructors) demonstrate the fishtail kick. Later, in 1916, Armbruster attended another of these swim carnivals, in which various entertaining stunts were performed involving imitations of animals. In it, Corsan performed a "butterfly" stroke by swimming the breaststroke kick and fluttering his hands at his sides on the surface of the water, not above the water. That stunt bore little resemblance to today's butterfly overarm stroke, yet its name may have subliminally registered with Armbruster.

Most importantly, at a subsequent swimming exhibition, Armbruster witnessed a young boy perform what he called the *Italian crawl*: a double overarm pull combined with the standard breaststroke (frog) kick. Although unsanctioned by the Amateur Athletic Union, that arm motion was used in many later exhibitions and, after certification, in competitions. The seeds may thus have been sown for future breaststroke development.

While coaching at Iowa, Armbruster had empirically determined that performing the breaststroke with the butterfly pull and the orthodox frog kick proved to be a poor mechanical combination. The kick was actually a retarding action compared to the faster, more powerful action of the flying arms. To take full advantage of the increasingly popular overarm stroke, something had to change. But, what?

Beginning in 1932, Armbruster began to put the pieces together. In a 1935 article coauthored with Sieg, Armbruster described the way he went about connecting and integrating the overarm stroke with the dolphin kick:

> One day in a moment of relaxation and play, [I] saw Jack Sieg go under water, lie on his side, with his arms trailing at the sides, imitating a fish, imitating the undulating movement with his head. I have often seen boys do this in water but never saw anyone derive the speed that Sieg was able to attain from it. We then tried it with the body face down, and the result was even greater. We then had him do it for speed against some of our best flutter-crawl kickers—no one could beat him. This was very impressive, to say the least. He then tried the double over-arm recovery of the breast stroke using this kick with it for several strokes. The leg rhythm was a natural movement

> and adapted itself perfectly to the rhythm of the double overarm recovery. We then started to train for longer distances and adjust the breathing in order to cover one hundred yards. Several weeks practice brought results of greater speed, but at the cost of greater energy output. The stroke is an exhausting one.

The team of Armbruster and Sieg eventually called the innovative merger of these two techniques—the butterfly overarm recovery plus two dolphin kicks—the *dolphin butterfly breaststroke*. But, their work was far from finished. Because the entire kick is performed underwater, Armbruster conducted additional mechanical analysis with the aid of slow-motion pictures, taken both from five windows below the surface of the water and from above the Armory's smaller 20-yard pool. Further experimentation produced several additional refinements, which in turn yielded still greater boosts in speed while better conserving the energy of the swimmer.

By concentrating on the process rather than the product of innovation, behavior emerges as the very center of creative human endeavor.

Going Mainstream

The new butterfly stroke generated considerable controversy because it did not comply with prevailing breaststroke rules, leading to its painfully slow acceptance by the competitive swimming community. By special permission, the full butterfly stroke was first used in the medley relay in a dual swim meet with the University of Wisconsin on February 25, 1935. The Iowa team included Dick Westerfield swimming the backstroke leg, Sieg swimming the butterfly in place of the standard breaststroke, and Adolph Jacobsmeyer swimming the freestyle. Sieg's time was some five seconds faster than the best previous 100-yard breaststroke!

Soon thereafter, Armbruster attempted an even more persuasive demonstration. At the 1935 NCAA meet at Harvard University, Armbruster staged an exhibition for the Rules Committee of what he then called the *dolphin breaststroke*. Sieg impressed the committee members with his demonstration of the new stroke, but they did not alter the NCAA rules to allow for the breaststroke variation. Armbruster's efforts over the ensuing years continued to be unsuccessful. Only in 1952 did the Fédération Internationale de Natation (FINA) sanction the butterfly stroke as a new event. Finally, in 1956, it was added to the Olympic Games in Melbourne, Australia, as a separate competition.

Over the years, swimmers and coaches have continued to refine and develop the butterfly stroke. It is now the second fastest stroke in the water after the freestyle. And, to many swimming fans, it is the most exciting.

While Armbruster and Sieg were developing the butterfly stroke, they were also experimenting with a new and faster turn, which they called the *tumble* or *flip turn*. In 1938, the pair believed they had perfected the maneuver and used it for the first time in the NCAA Championships at Rutgers University. Their innovation is still the fastest turn in the water; it is currently used by all speed and distance swimmers.

In a 1968 letter to Buck Dawson, executive director of the Swimming Hall of Fame, after being named the 1966 Honor Coach, Armbruster confessed that, "As I ponder over all of [my] awards and thrills, I will choose the creation of the Dolphin Butterfly stroke and the 'flip' turn as giving the greatest source of satisfaction. These two creations will live long, and beyond my time in the swimming world."

In the 1936 *Esquire* article, Larcom made a point that should be stressed: namely, how these important evolutionary changes in swimming actually came about.

> These latest in streamlined swimming strokes are developing out of their incipient stages. Speed becomes greater because waste motions have been discovered and eliminated and the strokes have been polished to smooth precision. [Although other strokes have continued to evolve] it is the breast stroke . . . that has had the most universal development.

As in countless other areas of human endeavor, trial and error assumes center stage in the unfolding of behavioral innovation. No one—not even Armbruster or Sieg—could have envisioned the final result of their extensive aquatic experiments. Today's butterfly swimmers—including Michael Phelps—may have little knowledge of the stroke's origins. But, if we are to gain a proper appreciation of this significant sporting achievement, its history is essential. Given that extended history, it is obvious that today's butterfly stroke is no "stroke of good luck"!

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Scientists' Nightstand

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ALSO IN THIS ISSUE

INVENTING THE ALPHABET: The Origins of Letters from Antiquity to the Present. By Johanna Drucker.
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ONLINE

On our *Science Culture* blog:
americanscientist.org/blogs/science-culture

On the Edge of Danger
Katia and Maurice Krafft were volcanologists who spent more than 20 years filming and photographing volcanoes and their eruptions, often risking their lives to learn just one more thing. The documentary *Fire of Love* explores their all-consuming commitments to each other and to volcanoes, and includes awe-inspiring footage of volcanoes and eruptions.



Image: Est

The Doors of Animal Perception

Lars Chittka

AN IMMENSE WORLD: How Animal Senses Reveal the Hidden Realms around Us. Ed Yong. 449 pp. Random House, 2022. $30.

I would love to own a time machine, not (just) to travel back to the Cambrian Period, but also to meet the scientists of the future and the past and discuss with them what they might make of our present state of knowledge. High on my list of people to speak with would be John Lubbock, who discovered in the 1880s that ants can see ultraviolet light and that they communicate via a chemical "language." In his 1888 book *On the Senses, Instincts, and Intelligence of Animals*, Lubbock wrote that "we find in animals complex organs of sense, richly supplied with nerves, but the function of which we are as yet powerless to explain." To animals, he noted, the world "may be full of music which we cannot hear, of color which we cannot see, of sensations which we cannot conceive."

Lubbock's research provided the first scientific glimpses into nonhuman animal perception. A number of additional sensory capacities outside those accessible to humans are now common textbook knowledge—for instance, ultrasonic sonar in bats, sensitivity to magnetic fields in migrating birds, and infrared sensors in nocturnal snakes. If I were tasked with getting Lubbock up to speed regarding what is known about animal sensory abilities today, I'd hand him Ed Yong's recent book, *An Immense World: How Animal Senses Reveal the Hidden Realms around Us.* I have no doubt that Lubbock would be thrilled beyond words by what has been discovered.

An Immense World is a hugely entertaining and insightful tour de force, a sort of Alice-in-Wonderland journey into the world as perceived by animals. It is written by a science journalist in a manner that is fully accessible to nonexperts. As a scientist who studies (and teaches about) animal sensory systems, I was impressed by Yong's ability to explain inherently complex subjects accurately, without unduly simplifying matters. I tend to be wary of kibitzers offering their views on the "alternative realities" of animals, particularly if they speak of finding it remarkable that the world we perceive is not "reality," as if other types of sensation indicate the existence of some metaphysical parallel universe or mean that the world we see is actually an illusion. Yong deftly steers clear of any such cheesiness.

He points out that such terms as *ultrasound* and *ultraviolet* can mislead us by making certain frequency ranges appear to be special just because they are outside the spectrum that is perceptible by humans. But humans may be unusually impoverished in some sensory areas. For instance, the vast majority of animal species can see ultraviolet (UV) light, and humans (along with a minority of other animals) are "special" only in their inability to do so. Yong calls out instances in which such terminology has led even scientists to fall victim to undue simplifications and misconceptions. A century after Lubbock discovered that ants can see shorter wavelengths than we can, such sensitivity was discovered, and subsequently fetishized, in vertebrates. For the sole reason that humans cannot see UV light, the ability of other animals to do so appeared to some scholars to enable a special "hidden" communication channel. The result was a wave of wholly unsurprising findings—such as that animals with UV color receptors use them (for instance, in choosing a mate)—and some bizarre ones: for example, the (now disproven) claim that birds of prey locate their



Neon-blue eyes dot the rims of a bay scallop shell. Each eye contains two retinas and is on a tentacle that allows it to move around and explore the environment. The way that scallops see the world differs drastically from human perception and is one of the many distinctions in sensory perception explored in Ed Yong's book. From *An Immense World*.

rodent victims by looking for UV reflectance emanating from rodent urine.

Yong highlights the absurdity of this approach by imagining what a bee might say in a similar situation:

> If bees were scientists, they might marvel at the color we know as red, which they cannot see and which they might call "ultra-yellow." They might assert at first that other creatures can't see ultra-yellow, and then later wonder why many do so. . . . They might wonder whether the large bipedal animals that see this color exchange secret messages through their flushed cheeks. They might eventually realize that it is just another color, special mainly in its absence from their vision.

An Immense World contains a riot of entertaining scientific findings that have stood the test of time. It is also scientifically comprehensive and up to date. The book is clearly useful not just to members of the public interested in science but to experts in zoology. It even includes a good number of findings that I was unaware of. For example, we are introduced to the thirteen-lined ground squirrel (called that because it has 13 black stripes down its back), which, because of a few mutations in a cold sensor, can survive for months at temperatures close to freezing, and when placed on a heatable plate, it won't step off until the surface reaches 55 degrees Celsius. Of all the species that have been tested, the thirteen-lined ground squirrel and the Bactrian camel have the least-sensitive versions of a sensor that detects painful heat.

If you are a scientist stuck in the minutiae of studying a particular sensory system, it is easy to lose sight of the big picture, and to lose touch with the sense of wonder evoked by studying how the world looks from inside the cockpit of another creature. If your day-to-day grind includes (as mine does) turf wars with colleagues about such things as which particular nonlinear equation to use for converting sensory input into receptor neural signals, then Yong's book will give you occasion to stand back and say, "Yes! This is why I am in this field, and I love it!"

Yong has met many of the field's heroines and heroes, and he describes them as a beautiful tribe of scientists driven by the excitement and joy of discovering unexpected facets of the natural world. These scientists stand in sharp contrast to the run-of-the-mill consortium grant science that funding agencies now often seem to favor—where huge money is converted into publications with more than 100 authors but only marginal gains in terms of pushing the boundaries of science. In the field portrayed in *An Immense World*, many of the most important discoveries are being made by individuals who are motivated solely by curiosity, using creative methods and technology they developed themselves rather than the off-the-shelf equipment used in mainstream labs. For example, one of the scientists Yong describes, Eric Warrant, hunts nocturnal bogong moths in Australia with a contraption he calls the Eye of Sauron. Warrant has performed experiments in which he put the captured moths into an insect flight simulator surrounded by large magnetic coils and then tried to subvert their navigation in various ways. By doing this, he was able to demonstrate that bogong moths achieve their migrations of more than 1,000 kilometers by sensing Earth's geomagnetic field, using an ability referred to as *magnetoreception*.

Some of the scientists Yong introduces us to are perceptually divergent, and he wonders whether experiencing the world differently from other humans is what has prompted these scholars to be curious about the diversity of animal senses. He mentions Michael Supa, a blind psychologist who demonstrated in the 1940s that he and other students who were either blind or blindfolded could detect obstacles using their hearing. The researchers exploring bat sonar at the time were aware of Supa's work and may have been influenced by it. When the term *echolocation* was coined in 1944, it was applied to the skills not just of bats but of blind people.

An Immense World is organized by sensory modalities: There are chapters on smells and tastes, light, color, pain, heat, contact and flow, surface vibrations, sound, echoes, electric fields, and magnetic fields. Yong points out that the Aristotelian segregation of the senses into vision, touch, hearing, smell, and taste is both incomplete and misleading. For example, hearing, like touch, uses mechanoreceptors; also, scientists still can't agree on what actually distinguishes the senses of smell and taste. The book has no in-text citations, but the endnotes and bibliography, which fill 68 pages, include the most important key sources.

The book ends with a melancholy lesson about sensory pollution of the environment caused by humans. When we hear the term *pollution*, we usually think

of the kind of chemical contamination that poisons plants and animals. But humans mess with the environment in all sensory modalities. That we are losing the night through excessive use of too-bright electric light sources in our cities and beyond has been much discussed; this light pollution disrupts the diurnal rhythms of animals, their communication, their navigation, their search for mates, and their life expectancy. Sound pollution is also common. The noises from our cities and from transportation interfere with sound signaling between animals. The level of low-frequency noise from ocean shipping has increased by a factor of 32 since World War II, and Yong lists some of the results:

> As ships pass in the night, humpback whales stop singing, orcas stop foraging, and right whales become stressed. Crabs stop feeding, cuttlefish change colors, damselfish are more easily caught.

The list of pollutions continues for all sensory modalities. But because these changes have taken place gradually over the past century, humans are behaving like frogs in a pot of water that is coming slowly to a boil. As sensory pollution has increased and species have gradually disappeared, we have come to accept each stage as a new normal.

Yong points out that there is still time to reverse these trends. There are many reasons to do so, including some that are in our own best interest. Noise affects human stress levels and our ability to sleep. Illuminating our settlements so brightly that they can be seen from space wastes both energy and money, and, contrary to what is sometimes alleged, there is no evidence for a link between crime and "poor" city lighting.

Many of us spend enormous sums of money to travel to distant but "serene" nature spaces. Yong builds a convincing case that we can have such environments at our fingertips, if only we take appropriate steps. Doing so will preserve the diversity of sensory worlds in the animal queendom, of which we are a part, and will enrich us in multiple ways.

Lars Chittka is a professor in the Department of Sensory and Behavioural Ecology at Queen Mary University of London and is the author of The Mind of a Bee *(Princeton University Press, 2022). His research interests include the color vision and cognitive abilities of bees, and their interactions with flowers.*

Writing History

Brian Hayes

INVENTING THE ALPHABET: The Origins of Letters from Antiquity to the Present. Johanna Drucker. 380 pp. The University of Chicago Press, 2022. $40.

Johanna Drucker has given her book a title in which the smallest word carries the heaviest weight. To speak of inventing *the* alphabet is to imply there is only one alphabet in all the world—despite the bafflement of English-speaking tourists confronting street signs in Athens or Moscow or Cairo. Drucker makes the point explicitly in her introduction:

> Ask the average literate person about the alphabet and often the response is, "Which alphabet? Our alphabet? You mean the Greek alphabet?" In fact, the alphabet was invented only once, by Semitic speakers in the ancient Near East. Alphabetic scripts all derive from the same root; as they spread, their letterforms were modified. Even scripts as visually distinct as Arabic, Cyrillic, Latin, Greek, Hebrew, Devanagari, Tamil, and Gheez have a common source.

Drucker's view shines a spotlight on the alphabet as a cultural artifact of extraordinary antiquity and importance. The graphic forms of the letters have varied and evolved. So have the mappings from written symbol to spoken sound. A few letters have been added and others have been dropped in some linguistic communities. But through it all, the alphabet has somehow maintained its integrity, even as civilizations and their languages come and go.

Today, variants of the alphabet form the writing systems commonly used to represent almost all the world's living languages. The major exceptions are the languages of China, Korea, and Japan.

The genre of *Inventing the Alphabet* is not history but historiography. The book's primary aim is not to investigate the origin of the alphabet but to record the progression of ideas about that origin, as they evolved over a span of millennia. Looking back from the present moment, much of the story reads as a catalog of fallacy and error. Before the 19th century, writers on alphabetic history had little material evidence to guide them, and in many cases, they had ideological or theological commitments to *mis*guide them. Drucker treats these flawed theories with care and respect, placing them in their historical context, rather than judging them by present-day criteria. She is less forgiving of a few 20th-century commentators whose falsehoods seem to reflect a willful disregard of evidence.

Curiously, the earliest surviving account of alphabetic origins got the story mostly right. The Greek historian Herodotus, writing around 440 BCE, states that the alphabet was brought to Greece by Phoenician settlers. Herodotus is vague about the time of this cultural exchange, and also about who the Phoenicians were, and from where they came. Nevertheless, later research has confirmed the key fact that the Greek alphabet derives, with some alterations, from a much older Phoenician one.

Between Herodotus and the era of modern scholarship lie two millennia of unconstrained speculation, some of it astute, some asinine. One recurrent theme concerns the story of Moses on Mount Sinai. When he received the stone tablets inscribed with the Ten Commandments, in what alphabet were those laws written? Some medieval and Renaissance authors postulated that the script of the tablets was humanity's first written language, and so our alphabet must be viewed as a direct gift from God. As late as the 18th century, the novelist Daniel Defoe defended this assertion with a highly imaginative argument: If writing had existed earlier, we would have received more detailed descriptions of prior events such as the drunkenness of Noah. Drucker comments that "Defoe could not resolve the basic contradictions that lingered: if writing did not exist before Moses received the Tablets, then how could he and the children of Israel read the Laws?"

The search for biblical validation of alphabetic origin stories was at least focused on the right part of the world. Others looked farther afield. In 1569, the Dutch writer Johannes Goropius Becanus insisted that a dialect of Flemish was the language of Adam, and in 1764 Gaelic nationalist Rowland Jones believed the first writing was in a Celtic script. Attempts to claim the alphabet as a trophy accomplishment of certain

ethnic and linguistic groups continued into the 20th century, and turned sinister with the contention that the credit should go to a (fabricated) Aryan race rather than the Semitic peoples of the eastern Mediterranean.

What transformed the study of the alphabet into a scientific enterprise, Drucker writes, was the flowering of systematic archaeology, starting in the 19th century and continuing today. Simply put, more digging produced more data. The number of alphabet specimens from the crucial period—the second millennium BCE—is still only in the hundreds, but it's enough for Drucker to express confidence about the identity of the originators. They were people of the land of Canaan, occupying the coastal cities of Tyre, Sidon, and Byblos, in territory that roughly corresponds to the modern nation of Lebanon. Their language was in the Semitic family but distinct from ancient Hebrew. These people were indeed the ones we know as the Phoenicians, although that's not a name they applied to themselves.

Curiously, the oldest known alphabetic inscriptions, discovered only in recent decades, are found not in the homeland of the Phoenicians but in Egypt and in the Sinai Peninsula (which was then, as now, controlled by Egypt). These writings, carved or scratched in soft stone, are written in a Semitic language but show the influence of Egyptian hieroglyphics. Given this evidence of bilingualism, the graffitists were probably more than casual travelers passing through Egyptian territory; Drucker suggests mercenaries, workers, or slaves. She offers a thumbnail summary of the current state of knowledge: "The alphabet was formed in the context of cultural exchanges between Semitic-speaking people from the Levant and communities in Egypt after or around 1800 BCE."

Drucker is a diligent and accomplished scholar, and is currently the Breslauer Professor of Bibliographical Studies at the University of California, Los Angeles. She is also an artist, a typographer, and a book designer. *Inventing the Alphabet* is an eye-opening synthesis, distilling an immense body of work by hundreds of authors and researchers. In fact, she reports that the project began more than 40 years ago, in her first year of graduate study. Given this broad scope, it seems churlish to ask for more, but I could not help noticing that almost all the sources are European. It would be interesting to hear more from the Arabic and South Asian communities who share our alphabetic heritage.

Drucker's central claim that the alphabet was only invented once is surely true; all of the alphabetic scripts known today can be traced back to the Phoenician characters. But it's another matter to suggest that the differences between modern scripts are minor enough that we can still speak of *the* alphabet. One might as well say that because life on Earth emerged only once, there is only one life-form on the planet today. In this respect, Drucker sometimes overreaches. For example, she dismisses arguments that the Greek alphabet stands apart from its predecessors because it was the first to include distinct letters for vowels. She may be right to do so, but she does not supply detailed arguments in support of that position.

The fact that all alphabets come from the same source is in itself intriguing, and even disturbing. Why would such a useful device arise only once in all of human history? Perhaps the reason is that once the alphabet existed, there was no need to reinvent it. After all, the letters were never patented. But this is only half an answer. People who had no contact with Mediterranean cultures, such as those in the Americas, invented their own writing systems, but none of them chose to develop an alphabet. I can't help wondering what would have happened if the Phoenicians had not come up with their ingenious scheme for converting spoken language into a stream of written symbols. I can barely imagine the modern world without it.

Brian Hayes is a former editor and columnist for American Scientist. *His most recent book is* Foolproof, and Other Mathematical Meditations *(MIT Press, 2017).*

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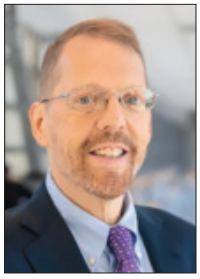
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John R. Jungck, Professor of Biological Sciences and Mathematical Sciences, Inaugural Fellow Honors College, Associate Director, Institute for Transforming University Education, Delaware Environmental Institute; Computational Biology and Bioinformatics, Delaware Biotechnology Institute

Mathematics Saves Lives! (G) • Citizen University (G) • Biomimetic Design Principles of Self-Assembling, Self-Folding, and Origami (G)



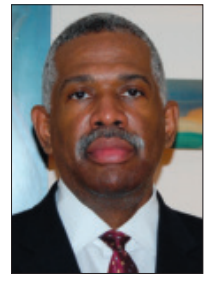
Akhlesh Lakhtakia, Evan Pugh University Professor and Charles Godfrey Binder Professor of Engineering Science and Mechanics, The Pennsylvania State University

What Can Engineering Scientists Do to Combat the Climate Emergency? (P, G) • Biologically Inspired Design for the Environment (P, G) • Optoelectronic Optimization of Thin-Film Solar Cells with Graded-Bandgap Semiconductor Layers (G, S)



Dante Lauretta, Regents Professor of Planetary Science and Cosmochemistry, University of Arizona

Life in the Cosmos: The Search for Biology in the Universe (P) • OSIRIS-REx: NASA's Sample Return Mission from Asteroid Bennu (G) • Journeys on the Asteroid Frontier: The Engineering Behind NASA's OSIRIS-REx Asteroid Sample Return Mission (S)



Steven Richardson, Professor Emeritus of Electrical and Computer Engineering, Howard University

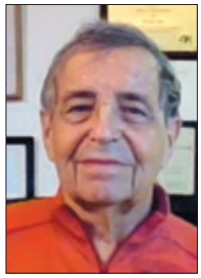
Using Supercomputers to Design and Understand Novel Molecules and Materials (P) • An Introduction to Quantum Computing (G) • Using Impurity-Vacancy Color Centers as Single Photon Emitters in Diamond (S)

P (Public), G (General), S (Specialized) **Details available at sigmaxi.org/lectureships**



Anne Savage, Founder and Executive Director of Proyecto Tití, Co-founder of Fundación Proyecto Tití, Santa Catalina at Hacienda El Ceibal Colombia

Proyecto Tití: Saving Colombia's Critically Endangered Cotton-top Tamarin (P, G) • Teens, Tamarins, and Teamwork: Successful Efforts to Engage Communities in Conserving Cotton-top Tamarins in Colombia (P, G) • Cotton-top Tamarins: Studies in Captive Care Have Informed Conservation Actions (P, G)



Michael S. Shur, Patricia W. and C. Sheldon Roberts Professor, Rensselaer Polytechnic Institute

Industrial Face of Nanotechnology (P, G, S) • Beyond Sunlight: Smart Light Emitting Diode Lighting (P, G, S) • Ultraviolet Light Emitting Diodes Saving Lives (P, G, S)



Ramteen Sioshansi, Professor, Department of Integrated Systems Engineering, Department of Electrical and Computer Engineering; Director, EmPOWERment National Science Foundation Research Traineeship Program, The Ohio State University

Technology Pathways to and Economic and Technical Challenges with Decarbonizing Electricity Systems (P, G, S) • How Regulatory Choices Impact the Sustainability, Reliability, and Resilience of Energy Supply (P, G, S)



Fred H. Smith, University Professor of Anthropology and Biological Sciences Emeritus, Illinois State University

Visiting the Ancestors: Archaic Africans, Neandertals, and the Beginnings of People Like Us (P, G, S) • A Night Out with the Neandertals (P, G) • The Perplexing Case of the Vindija Neandertals (G, S)



Jeffrey Toney, Senior Vice President for Research, Kean University

The Undervalued Currency of Culture in Higher Education (P) • Science and Human Rights (G) • The Pandemic of Confusion (P)



George Veni, Executive Director, National Cave and Karst Research Institute

The World Below: An Introduction to Caves and Karst (P, G) • Sinkholes: Where They Occur, How They Form, and How to Minimize Their Impacts (P, G, S) • The Sunless Seas of Karst Aquifers (P, G, S)



Jut Wynne, Assistant Research Professor, Northern Arizona University

Addressing Knowledge Shortfalls in Subterranean Biology (P, G, S) • Evolutionary Dynamics of Subterranean-Adapted Fauna (P, G, S) • Science and Technology Requirements to Explore Caves Beyond Earth (P, G, S)



Enrico Zio, Professor, MINES ParisTech, PSL Research University, CRC, Sophia Antipolis, France, and Energy Department, Politecnico di Milano, Italy

Risk-Informed Decision-Making for Building a Society Resilient to Global Risks like the COVID-19 Pandemic (P, G, S) • The Future of Risk Assessment (S) • Machine Learning in Data-Driven Prognostics and Health Management (PHM) for Condition-Based and Predictive Maintenance (S)

P (Public), G (General), S (Specialized)

Details available at sigmaxi.org/lectureships

Chapter Subsidy Application Deadline:

March 1, 2023

sigmaxi.org/lectureships

January–February 2023 Volume 32 Number 01

Sigma Xi Today
A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

Call for Nominations

Sigma Xi, The Scientific Research Honor Society, is seeking nominations for qualified candidates to fill positions for President-elect, Board of Directors, Committee on Nominations, and Associate Directors for representation of regions and constituencies. The Board of Directors is principally responsible for managing the activities, property, and affairs of the Society in accordance with the policies established by the Assembly of Delegates. The Board of the Society simultaneously serves as the Board of the Corporation.

Sigma Xi's elected leaders are expected to meet the commonly held standards of professional ethics and scientific integrity and will be asked to sign our Code of Ethical Conduct to this effect. Sigma Xi seeks diverse and inclusive participation in all its elected and appointed positions. Sigma Xi's elected positions are voluntary.

PRESIDENT-ELECT:
Election to this position carries a full three-year term, each year with distinct title, duties, and responsibilities. Failure to complete any part of the term will end the term in full.

President-elect:
July 1, 2024–June 30, 2025
President:
July 1, 2025–June 30, 2026
Past-president:
July 1, 2026–June 30, 2027

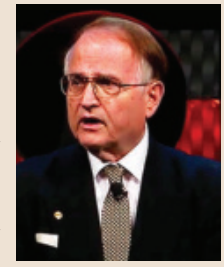
Nominations for President should be submitted to **elections@sigmaxi.org** by April 1, 2023.

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Sigma Xi Today is managed by **Jason Papagan** and designed by **Chao Hui Tu.**

From the President

How Science Addresses Important Disease Problems



The theme of Sigma Xi's recent International Forum on Research Excellence (IFoRE) was convergence, and appropriately, IFoRE brought together scientists from various backgrounds to address important medical and societal problems. One topic of lively discussion was how the outcome of disease treatment is influenced by the time of day of therapeutic agent administration. Over the past four decades, new findings have shown that the time of treatment is a crucial factor in therapeutics. It is now well established that nearly all functions of the body, including those influencing pharmacokinetic parameters, display significant daily variations or patterns. Researchers suspect that the chronological point of treatment may affect the outcome of a host of conditions, including hypertension, asthma, ulcers, arthritis, cholesterol, and even cancers.

New findings have led to the merging of disparate focuses into a new research area, that of chronopharmacology, which is the study of coordinating biological rhythms (chronobiology) with medical treatments. Chronobiology is the study of the temporal relationships of biological phenomena. Early 1970s data provided the first evidence that the "biological clock" is not fiction but is, in fact, genetically determined and can even be transplanted from one subject into another, thereby inducing the rhythmicity of the donor into the recipient.

Chronopharmacology takes a person's biological rhythms into consideration in determining the timing and sometimes the quantity of medication needed to optimize a drug's desired effects. Revising the dosing schedule, reformulating a therapeutic agent so its release into the bloodstream is delayed, or using programmable pumps to deliver medicine at precise intervals are some of the simple, chronopharmacology-inspired innovations that may lead to enormous benefits.

Many chronic and acute disorders have a prominent circadian pattern of symptom appearance. For example, allergic rhinitis is an early morning disorder, thrombotic stroke risk is greatest in the morning, and hemorrhagic stroke risk is greatest in the late evening. Many cardiovascular diseases seem to be affected by circadian rhythms, such as myocardial infarction, stroke, high blood pressure, and angina pectoris.

The science seems clear that administration of therapeutic agents at different times of the day has a significant impact on medical outcomes. This burgeoning field of chronopharmacology also adds credence to the concept of convergence science—that is, fully integrating different areas of science to solve complex research problems that focus on societal needs and pressing health challenges. Convergence, one of the National Science Foundation's "10 Big Ideas," was explored deeply at IFoRE. If you missed the conference, keep an eye out for ways that members can access recorded content from the IFoRE sessions, a benefit of being an active member of Sigma Xi.

Nicholas A. Peppas, ScD



Edith Gonzalez presents "The Story Collider" during #SciCommSunday luncheon



Ellice Wallace presents on diversity and inclusion in science communication



2022 Sigma Xi Fellows Ceremony



Bruce Alberts receives the 2022 Gold Key Award



Selfies and networking at the GIAR 100 Reception

IFoRE
POWERED BY SIGMA XI

Sigma Xi's new annual conference, the International Forum on Research Excellence (IFoRE), made its highly anticipated debut November 3–6 in Alexandria, Virginia. Scientific minds spanning multiple generations and disciplines converged to share research, make connections, celebrate awards, and discuss a variety of themes including diversity, inclusion, and science communication. Thanks to the 500+ attendees who brought energy, ideas, and inspiration to the event. We look forward to seeing everyone in Long Beach, California, for IFoRE '23!



Students celebrate in the IFoRE ballroom lobby after receiving awards



Rena Bizios is presented with the 2022 Procter Prize



Poster presentations at the Student Summit



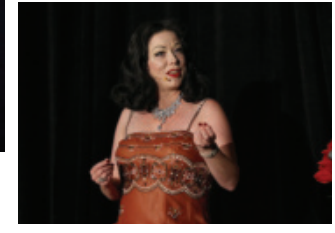
Key Thoughts host Liz Neeley



Key Thoughts speaker Gilda Barabino



"Curious Conversations" with Robert T. Pennock and Bruce Alberts



Heather Massie performing as Hedy Lamarr

Student Researchers Awarded at IFoRE Student Summit

Sigma Xi inducted 46 students as new members of the Society during a banquet ceremony on Saturday, November 5, 2022. The students were award recipients for oral and poster presentations at the 2022 IFoRE Student Summit in Alexandria, Virginia. Cash prizes were given along with commemorative medals and membership to the Society, including one year of paid dues. Over 250 high school, undergraduate, and graduate students attended the inaugural conference, and research was presented in oral and poster format, both in-person and virtually. A judging committee of Sigma Xi members evaluated the in person presenters on their scientific thought, methods, and communication skills. In addition to the judges' awards, the DC chapter of Sigma Xi sponsored two Student Choice Awards, carrying additional monetary prizes and voted on by fellow participants.



2022 Student Summit award winners:

Top High School Poster Presenters
Hadley Edwards
Valerie Fan
Zachary Harpaz
Sydney Krusch
Deeksha Kumaresh

Top Oral Presentations
High School
Likhitha Selvan
Undergraduate
Gabriel Ohmes and Nathan Couch
Graduate
Cody Howe

Top Undergraduate Poster Presenters
Sara Aly and Michael Rosario
Amerti Guta
Alexia Johnson
Jasmine Johnson
Madeleine Sorbonne
Angela Youn

Top Graduate Poster Presenters
Julia Brandenstein
Siobhan Branfield
Barbara Flasz
Morgan Markel
Elissa Moller
Mafia Mahabub Rumpa
Hala Samara
Jack Sytsma
Michael Trapani and Danielle Werts

Student Choice Awards
First Place:
Zechang Yang and Tyler Kim

Second Place (Tie):
Javier Menendez
Deneen Royal and Khali Crawford

Interdisciplinary Research Category Winners (oral presentations)
Yasmeen Hassan
Calvin Mathew
Priyanka Supraja Balaji
Gabriel Ohmes and Nathan Couch
Likhitha Selvan
Rebecca Adler

Interdisciplinary Research Category Winners (poster presentations)
Aaron George
Daniel Wilentz
Sasha Masson
Shria Halkoda
Uma Nath
Hala Samara
Mafia Mahabub Rumpa
Michael Trapani and Danielle Werts
Julia Brandenstein
Deneen Royal and Khali Crawford
Sreya Sandal
Javier Menendez

Call for Nominations

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The following positions carry three-year terms beginning July 1, 2024, and ending June 30, 2025.

BOARD OF DIRECTORS:
Baccalaureate Colleges Constituency Group (BA)
Canadian/International Group Constituency Group (CI)
Northwest Region (NW)
Southeast Region (SE)

ASSOCIATE DIRECTORS:
Membership at Large Constituency Group (MAL)
Research & Doctoral Universities Constituency Group (R&D)
North Central Region (NC)
Southwest Region (SW)

COMMITTEE ON NOMINATIONS:
Three-year term beginning immediately following the 2022 elections.
Area Groups, Industries, State & Federal Labs (MI)
Comprehensive Colleges & Universities Constituency Group (CM)
Mid-Atlantic Region (MA)
Northeast Region (NE)

Nominations for the Board of Directors, Associate Directors, and Committee on Nominations should be submitted to **elections@sigmaxi.org** by June 30, 2023.

Active full members of Sigma Xi are eligible to run for office. An inactive member may become active at any time through payment of current dues. Self-nominations are welcomed.

The election will take place electronically by ballot immediately following the November 2023 International Forum on Research Excellence (IFoRE). Please visit **sigmaxi.org/elections23** to view the lists of duties and responsibilities for each position.



IFoRE

POWERED BY SIGMA XI

International Forum on Research Excellence

Save The Date

November 9–12, 2023
Long Beach, California

SCIENTIFICS DIRECT®

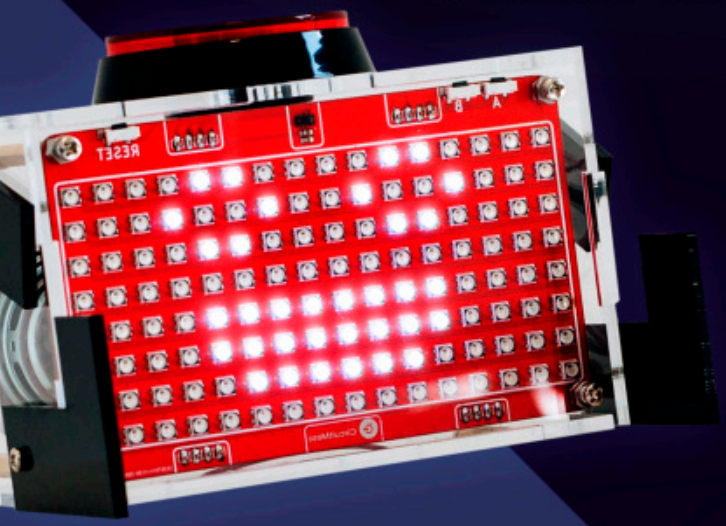
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CHATTER

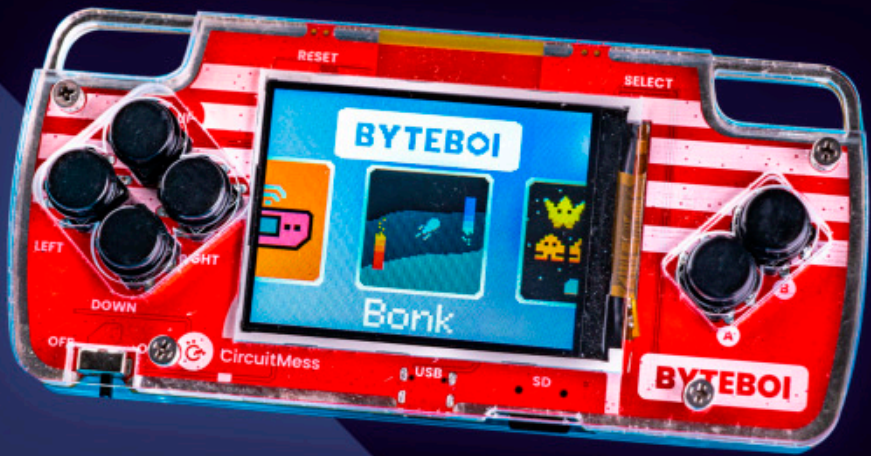
Wireless end-to-end encryption gadgets

SPENCER

Assemble your very own personal voice assistant

BYTEBOI

Microcomputer to code & play your own video games



An Unbelievable Selection of Electronics Kits at www.ScientificsOnline.com